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US Army Corps of Engineers
Waterways Experiment Station

Proceedings, Second North American Workshop on Modeling the Mechanics of Off-Road Mobility

by D. A. Horner, G. L. Mason, Niki Deliman, R. A. Jones

WES

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Prepared for U.S. Army Research Office

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Final report

Prepared for U.S. Army Research Office
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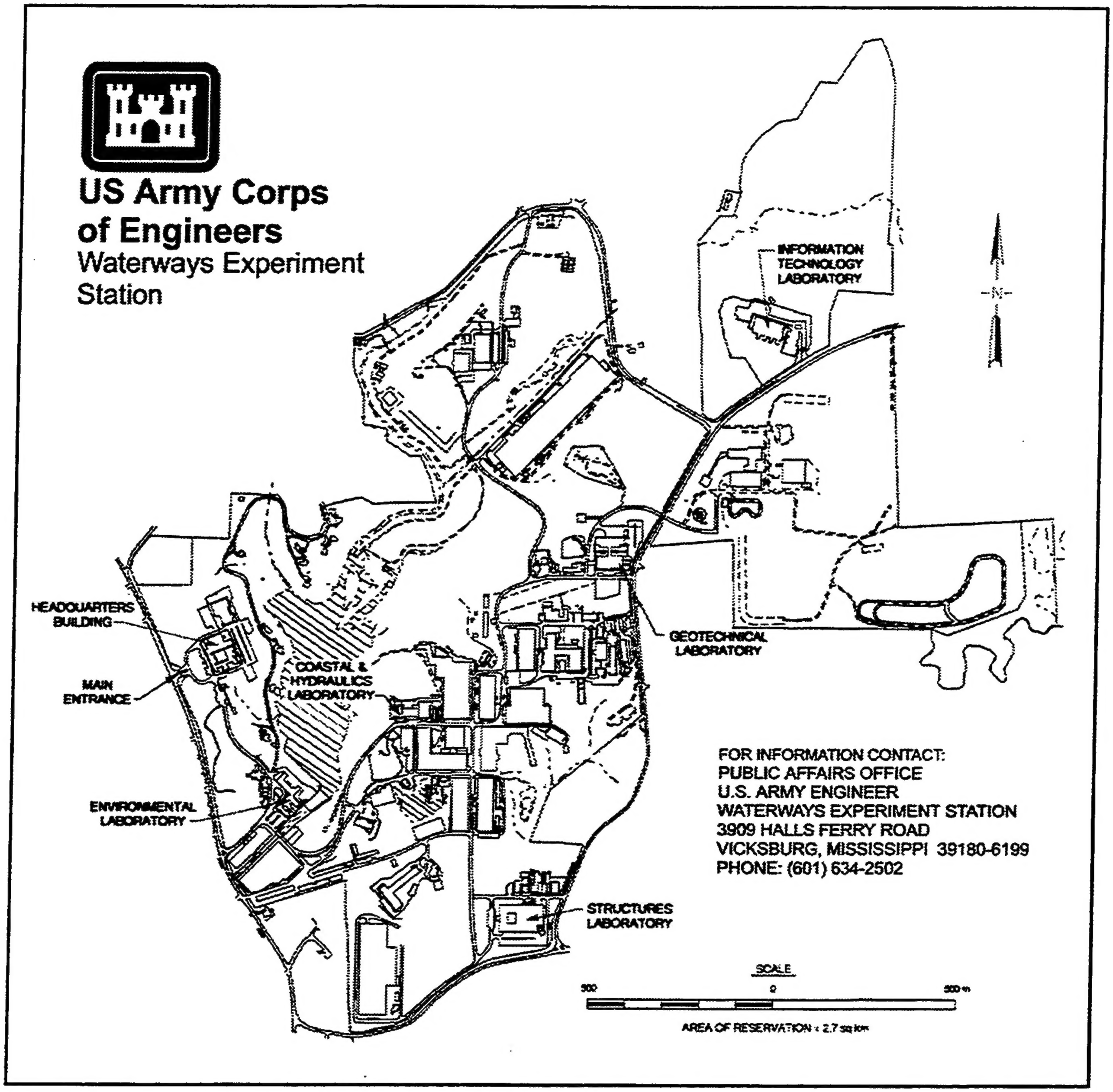

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Contents

Preface

The Second North American Workshop on Modeling the Mechanics of Off-Road Mobility was held 13, 14, and 15 March 1996 at the U. S. Army Engineer Waterways Experiment Station (WES) in Vicksburg, MS. The workshop was sponsored by the U. S. Army Research Office under the Terrestrial Science Program of the Engineering and Environmental Sciences Division.

The workshop was organized by Mr. David A. Horner, Dr. Niki C. Deliman, Mr. George L. Mason, and Mr. Randolph A. Jones, under the general supervision of Mr. Newell R. Murphy, Chief, Mobility Systems Division (MSD), Geotechnical Laboratory (GL), and Dr. William F. Marcuson III, Director, GL. This report which documents the proceedings of the workshop was prepared by Dr. Deliman, Messrs. Horner, Mason, and Jones with the assistance of Ms. Susan Sippel.

The workshop organizers wish to thank Mses. Dorothy L. Staer, Debra S. Alexander, and Rachelle Green for assisting in the organization of the workshop. The workshop organizers would also like to thank Mr. Burhman Gates for creating the homepage for the workshop to ensure that the international community had access to information regarding the conference.

Dr. Robert W. Whalin was Director of WES during the preparation and publication of this report. COL Bruce K. Howard, EN, was Commander.

1 Introduction

Background

Off-road mobility performance is a crucial component of U. S. Military operations involving ground vehicles. Military vehicles are often deployed in regions where mobility is limited. Thus, evaluating mobility over a wide range of conditions and geographic regions is an important aspect of vehicle design and modification. Furthermore, mobility assessment of existing vehicles prior to deployment is also essential. Comprehensive testing on proving grounds throughout the United States is conducted to insure the quality and performance standards of each vehicle. While testing of vehicles is considered the best way of evaluating vehicle performance, with current downsizing of the military, supplemental methods are being considered. The computer modeling of vehicle performance in a Virtual Proving Ground (VPG) is among the most promising and technically challenging of these alternatives.

The VPG is a relatively new term applied by the modeling and simulation community to describe the duplication of vehicle performance in actual environments, such as test areas found at Army proving grounds, via computer technology. The VPG concept entails generating surrogate test courses or regions of interest in a digital library as defined by relevant environmental factors. A key element of the VPG involves linking the surrogate test courses with vehicle models to simulate vehicle - terrain response and capture performance measures. For example, tests that evaluate ride quality, achievable speed, engine performance, and obstacle crossing, among other characteristics, can be conducted on the computer. The goals of VPG extends beyond the needs of the procurement community and address those of the combat community to support simulations in a Distributed Interactive Simulation (DIS) environment.

The vision behind these virtual environments is to provide a rapid assessment of the vehicle performance in any area of the world, to reduce vehicle design life cycles, and to enable cost effective field testing. There are immense opportunities for contributions to the VPG through scientific or technological advancements relating to vehicle-terrain interaction. This workshop was designed to bring together industry, university, and government leaders to assess the current state of the VPG, identify current and future requirements, and define the direction for future research to meet these needs.

Purpose

The Second North American Workshop on Modeling the Mechanics of Off-Road Mobility was organized by the U. S. Army Engineer Waterways Experiment Station (WES), Mobility Systems Division (MSD) for the purpose of convening experts in areas related to vehicle-terrain interaction and identifying future research needs to support modeling in virtual environments. The workshop was held from 13 through 15 March 1996 at WES. Representatives from academic institutions, government agencies, and private industry were in attendance. The workshop format included formal presentations, panel discussions, and group interaction to facilitate meeting the objectives.

Three questions were posed to participants as focus items to consider during the conduct of the workshop: (a) What are today's capabilities in off-road mobility related to virtual environments? (b) What should the VPG be capable of or consist of in five years?, and (c) What are the technical barriers to achieving these capabilities in five years? Presentations and discussions herein are related to one or more of these themes.

The purpose of this report is to summarize workshop results and to compile material presented by invited speakers. Not all presentations were accompanied by papers as this was not required. The report is organized as follows. Workshop organization and results are presented in Chapter 2. The program is given in Appendix A. Appendix B contains papers given during the historical addresses. Papers presented by many of the invited speakers are contained in Appendix C and presentation slides provided by speakers not submitting papers are contained in Appendix D.

2 Workshop Summary

Workshop Organization

The workshop was organized into four sessions or panels: Session 1 - Virtual Proving Ground, Session 2 - Virtual Environments, Session 3 - Basic Mobility Research, and Session 4 - Modeling Considerations. Additionally, on the first and second days of the workshop, historical addresses were presented during general sessions for the purpose of providing perspective on origins and progressive advancements in the field of off-road mobility research. Each session included an initial overview presented by the session moderator and contained five to six presentations related to the session theme. Time for discussion was provided during each session as well as at the end of the workshop. The workshop was concluded with testing and technology demonstrations at WES. The program is shown in Appendix A.

The workshop began with a brief welcome by Director of the Geotechnical Laboratory and opening remarks by the workshop organizer. These were followed by the first of three historical addresses presented by distinguished former WES employees. In the first historical address, Mr. Warren Grabau discussed the evolution of quantitative terrain evaluation and the relationship to mobility. The second and third historical addresses were delivered on the second day of the workshop by Dr. Dean Freitag and Mr. Adam Rula, respectively. Dr. Freitag described the derivation of soil strength properties and testing techniques. Mr. Rula presented a historic overview of mobility testing. Upon their retirement from WES, each of these technical experts left behind a series of technical reports and algorithms which still remain as state-of-the-art for establishing mobility criteria for vehicles. The historical addresses are contained in Appendix B.

Session 1 - Virtual Proving Ground was the topic on day one of the workshop. Presentations centered on the concept and use of the VPG at several organizations, including U. S. Army Tank Automotive Research, Development and Engineering Center (TARDEC), U. S. Army Test and Evaluation Command (TECOM), and the University of Iowa. Issues encompassed the virtual prototyping process including optimal design and analysis, reliability and maintainability, modeling and analysis in virtual environments, integration of live and simulated testing, and development of person-in-the-loop feedback

capabilities. The development of virtual test courses, virtual instrumentation, and virtual test operating procedures are areas that impact and support these issues.

Session 2 - The Virtual Environments session took place on the second day of the workshop and was composed of six presentations focused on work related to characterizing VPG environments in terms of factors affecting mobility. Factors needed to model processes in the VPG must be appropriately represented so as to produce correct inputs, responses, and results. Aspects such as mobility factor estimation, rainfall and watershed simulation, measurement of snow properties, and contact pressure measurement were discussed. Extensions to modeling temporal and spatial variability of soil strength and the mobility factor considerations in testing were presented.

Session 3 - The Basic Mobility Research session was also conducted on day two of the workshop and involved six presentations concerning fundamental research in areas related to mobility. Research methods addressed included multi-scale constitutive theory, contact mechanics, discrete particle modeling, and discrete element methods. Vehicle-terrain interaction applications examined involved traction and land compaction among other issues.

Session 4 - The Modeling Considerations session took place on the final day with six presentations. This session focused on challenges such as how to evaluate vehicle performance, test vehicle performance criteria, measure and model soil - traction element shear, and account for uncertainty in parameter estimation in modeling. New performance measures addressing vibrational energy issues were proposed for reliability and maintainability assessment. Presentations on soil moisture estimation, innovative test methods, and stochastic mobility modeling showed the importance of incorporating statistical variation in VPG environments and simulations. The session illustrated the difficulties in measuring factors, such as shear strain at the soil-traction element interface, critical to mobility modeling.

Workshop Results

Through presentations and general discussions in the workshop the individuals assessed the current state of the off-road mobility modeling and work in supporting fields. The NATO Reference Mobility Model serves as a current standard for evaluating ground vehicle performance in the procurement community. Vehicle speed, mission rating speeds, and nogo areas are used as metrics. Vehicle driver simulators have been built to model vehicle response over non-deformable surfaces. Vehicle dynamics packages can be used to examine vehicle designs with mobility predictions.

While these models have been successfully used in the past, the idea of a VPG which standardizes the terrain and mobility impairments that a vehicle would encounter is considered a challenging area. The consensus of the

workshop is that a major problem facing the VPG is the ability to appropriately characterize the vehicle traction element interaction as a function of the dynamically changing environment. The overall view of the participants in the workshop was that while field testing would never cease completely, the VPG has the potential to greatly reduce testing. The general problems facing VPG to accomplish this task include:

a. How to model accurate and detailed soil information for the VPG.

b. How are the Proving Grounds characterized?

c. How do we create a library of vehicle characteristics and performance data?

d. How do we model environmental effects?

e. How to accurately model power trains.

f. What percent are human factors and what percent is a component of the test facility?

g. How to get vehicle characteristics in greater detail.

h. Does VPG get us through test cost and RAM requirements?

Participants of the workshops challenged the ability of current off-road models to simulate accurate steering forces of a vehicle, particularly when the ground deforms as with soft soils. Successful off-road VPG requires the development of soil-vehicle interaction models that accurately model the deformation, shear strength, and energy damping characteristics of real soils subjected to dynamic loadings. The workshop members also considered quantifying the physical characteristics of the terrain in terms of temporal and spatial changes a critical issue for accurate modeling of off-road vehicles. These will provide into the future direction of the private, academic, and federal sector.

Appendix A
Workshop Program

Program
Second North American Workshop on
Modeling the Mechanics of Off-Road Mobility

U.S. Army Engineer Waterways Experiment Station,
Vicksburg, MS
March 13-15, 1996

Sponsored by:
U.S. Army Research Office
U.S. Army Engineer Waterways Experiment Station

<u>WEDNESDAY 13 MARCH</u>

0800 - 0825	Registration, Mobility Systems Division Annex
0825 - 0830	Call to Order and Announcements (Mr. David Horner, WES)
0830 - 0845	Host Welcome (Dr. Robert Whalin, WES Director)
0845 - 0900	Workshop Focus Presentation (Mr. David Horner, WES)
0900 - 1000	Historical Address - Introduction (Mr. Newell Murphy, WES) "The Origins and Development of Quantitative Terrain Evaluation" Mr. Warren Grabau, WES
1000 - 1015	Break

SESSION 1: VIRTUAL PROVING GROUND

1015 - 1130	Moderator - Mr. Randy Jones, WES "Introduction to VPG" Mr. Randy Jones, WES "VPG (TARDEC)" Dr. Ron Beck, TARDEC
1130 - 1300	Lunch (WES Main Cafeteria) and Three-Screen Briefing
1315 - 1700	"VPG RAM" Mr. Leon Jokubaitis, TARDEC "VPG (TECOM)" Dr. Paul Oxenberg, TECOM "VPG (University of Iowa)" Dr. Peter Grant, University of Iowa

1900	Dinner at Ameristar Casino

THURSDAY 14 MARCH

0800- 0805	Opening Remarks - Mr. Newell Murphy, WES
0805 - 0915	Historical Address "Numeric Modeling of Terrain-Vehicle Interaction" Dr. Dean Freitag, Tennessee Tech "Historic Overview of Mobility Modeling" Mr. Adam Rula, WES
0915 - 0930	Break

SESSION 2: VIRTUAL ENVIRONMENTS

0930 - 1215	Moderator - Mr. George Mason, WES "Terrain Considerations for Testing MLRS Platforms" Mr. Brock Birdsong, MICOM "Measuring Contact Pressures of Vehicles" Mr. Robert Underwood, ARA "Mobility Factor Inference" Ms. Denise Bullock, WES "Terrain and Rainfall Simulation" Dr. Daniele Veneziano, MIT "Snow Properties and Measurements" Mr. Paul Richmond, CRREL "Spatial Temporal Considerations for Vehicle Traction" Mr. George Mason, WES
1215 - 1315	Lunch (WES Main Cafeteria)

SESSION 3: BASIC MOBILITY RESEARCH

1315 - 1630	(Moderator - Mr. David Horner, WES) "Soil Mechanics Research Needs for Mobility Modeling" Dr. John Peters, WES "Multiscale Constitutive Theory with Traction for Swelling Soils" Dr. John Cushman, Purdue University

"Contact Mechanics Applications for Terrain/Vehicle Interactions"
Dr. Antionette Tordesillas, Kansas State University

"Land Compaction Modeling"
Dr. Liqun Chi, Caterpillar

"Mechanical Systems/Terrains Potentially Addressable by Discrete Particle Modeling"
Dr. Peter Haff, Duke University

"Soil Plowing Using the Discrete Element Method (DEM)",
Dr. Roman Hryciw, University of Michigan and
Mr. David Horner, WES

FRIDAY, MARCH 15

0800- 0805 Opening Remarks

SESSION 4: MODELING CONSIDERATIONS

0805 - 1120 (Moderator - Dr. Niki Deliman, WES)

"NRMM Applications at TACOM"
Ms. Nancy Saxon, TARDEC

"Insights from Stochastic Mobility Modeling"
Dr. Niki Deliman, WES

"A Multipass Sinkage Model for Layered Soils"
Dr. Robert Walker, ARA

"Soil Moisture Prediction & Simulation Factors for Use in Mobility Modeling"
Dr. Elfatih Eltahir, MIT

"Field and Modeling Techniques"
Mr. Randy Jones and Mr. Greg Green, WES

"Techniques to Investigate Lateral Stability"
Dr. Nelson Funston, NATC

1120 - 1200 Workshop Discussion

1120 - 1230 Lunch (on your own)

1230 - 1500 Testing and Technology Demonstrations

Appendix B
Historical Overview Papers

No Traction - No Action

Dr. Dean Freitag

WES Retired

The ability of a vehicle to accomplish its task in any terrain is the product of a number of interactions. It is dependent on the characteristics of the vehicle, of the mission, of the terrain, and of the soil. I like to view the soil as an entity of itself - separate from terrain. Terrain will include topography, roughness, and vegetation. All the terrain factors are impediments to progress. Soil is the source of the driving force that the vehicle uses to overcome the impediments and accomplish its mission. Therefore, the soil-vehicle interaction is the basic equation of cross-country travel.

The first studies on problems of vehicle operations in difficult terrain tended to separate the soil from the vehicle. The primary objective was to create better vehicles. Vehicle designers sought uniform mud deposits or built special test pits to evaluate new concepts by comparative runs with another vehicle in the same soil. Later, when the Corps of Engineers became involved with the problem posed by the probable necessity to cross rice paddies in the invasion of Japan, they also thought first in terms of providing bridges, prefabricated surfaces, and traction aids. However, being pavement engineers, they also looked for means of measuring the bearing capacity of the soils upon which their structures were to be placed. They said they were measuring the trafficability of the soil.

Three instruments were tested for use in measuring the soil strength; an impact cone penetrometer (the North Dakota cone bearing test), a drive sampler

(the Porter sampler), and a spring-loaded bearing plate (the Engineer Board penetrometer). None were judged satisfactory but during the testing phase, a variation was developed that eventually evolved into the present cone penetrometer. The requirements that guided the selection of the instrument are listed in Table 1 below.

Table 1

Requirements for a trafficability test instrument

Military Characteristics	**Technical Characteristics**
Simple to operate	Get many values quickly
Light weight, portable	Measure to 24 in. depth.
Silent operation	Relate to performance
Waterproof	
Readable at night	
Operate from prone position	

Because of the need to study the influence of the soil, the Engineer Board, which had the responsibility for the study, got some help from the Waterways Experiment Station. Two soils experts, Charles R. Foster and Felton L. Bingham, were given the task of finding a means to measure the soil condition that required bridging and that which could be traversed by the vehicles alone. The time allotted for the study was extremely short and decisions had to be made with less than adequate data. The time frame is given in Table 2.

Table 2

Time Scale of First Test Program

Mid-January 1945	Engineer Board asked to study expedients for crossing swampy terrain
Mid-April 1945	Task redefined to specific problem of rice paddies.
Mid-May 1945	Plan of tests approved, logistics of tests at Yuma, AZ begun.
Mid-June 1945	WES involved, First test areas prepared.
31 July 1945	Testing essentially complete.
31 August 1945	Analysis complete and report prepared.
Mid-November 1945	Landings on Kyushu, Japan scheduled.

In spite of the compressed schedule, by the end of vehicle testing in July 1945, the usefulness of the cone index concept was fairly well established and most of the principles of soil-vehicle relations had at least been identified. These included the observations listed in Table 3.

Table 3

Principles of Operation of Vehicles in Soft Soil

The water content of a fine-grained soil is the primary factor in its trafficability.

Soils above their liquid limit will not support traffic of most vehicles.

Soils below their plastic limit will support traffic of almost all military vehicles.

Soils in between these two water contents are likely to inhibit vehicular travel.

The cone penetrometer is a satisfactory instrument for measuring the soil strength.

Repeated passes of a vehicle can materially change the trafficability of the soil.

Drawbar pull can be translated mathematically into slope climbing ability.

A vehicle will operate in soft soil up to a depth about equal to its ground clearance.

Vehicles can be placed into broad groupings on the basis of their mud mobility.

A vehicle can be assigned a number that rates its mobility.

Tracks with small bogies and minimal clearance can be jammed by accumulated sticky soil.

Wheeled vehicles without traction aids are vulnerable to slippery surface soils

This list marks just about every tree in the forest. The details needed to be worked out but the sign posts are all there.

One of the details that turned out to be quite significant was the change in strength of a soil as a result of the repeated application of stresses. The change could be either an increase or a decrease in the effective strength, but from the standpoint of mud crossing, only a decrease was critical. The general nature of the occurrence and the development of a test to evaluate the magnitude of the loss have been described in an earlier presentation.

The analysis showed that the Engineers realized the ability of a soil to support the passage of a vehicle was greatly dependent on the characteristics of the vehicle. Soon (1951) a system was devised to estimate the mobility rating number (called the vehicle cone index or VCI) for vehicles that had not actually been tested. The system calculated the VCI from basic vehicle data such as weight, ground clearance, power, and size of the traction elements. The relations

that evolved were rational in a broad sense but at heart were quite empirical Nevertheless, this provided a logic for altering a vehicle so as to improve its ability to operate on soft soils.

As you may be aware, the different branches of the Army sometimes guarded their fiefdoms rather closely. The Ordnance Corps was responsible for combat vehicles so they studied tank mobility. But, as they tried to improve the soft ground performance of their tanks, they had to deal with the properties of soils. They needed a soil measuring system.

At about this time (1950), a dynamic, articulate, and persuasive Canadian military officer by name of M. G. Bekker appeared on the scene. He devised an analytical approach to the evaluation of a vehicle on soft soil and proposed a soil test system that would provide the parameters needed. A shear test and a plate test were used to yield a set of seven soil values that could be inserted into the equations to derive predictions of the vehicles pull-slip curve and the amount of sinkage it would experience. Col. Bekker convinced the Ordnance officers in the US to adopt his system and to establish a laboratory to exploit the insights that would flow from this and similar concepts.

Thus began an era of non-cooperation that for years divided the research communities. Each faction pointed out the deficiencies of the other's system and tended to overlook the failings of its own. Actually, although there are differences in the analysis procedures, the heart of the conflict stems from disagreement over what constitutes an adequate measurement of the soil. However, as the years took their toll and the most determined proponents retired from the arena, a blending of sorts took place and the systems now coexist in relative harmony. Perhaps this is a time to revisit the scene and devise a better

approach by overcoming some of the faults of the previous ones. I am sure that is possible to do.

The cone index based system and the Bekker soil value system are not the only methods that have been proposed. The alternatives have found it difficult to demonstrate their superiority though, and have not found adherents. The one possible exception is the concept of similitude and scale-modeling pioneered by Nuttall many years ago and built on by others including the Waterways Experiment Station. However the requirement for a soil measurement is implicit even in modeling and the system doesn't really avoid the disagreement.

The principles of scale modeling, dimensional analysis, and similitude are the same. There is a fundamental assumption that the parameters describing a physical interaction of are made up of one or more members of a very limited set of fundamental dimensions. A general relation between the parameters can be formulated among those parameters only if the quantities are composed of the same dimensions. An analysis based on dimensional balance is qualitative rather than quantitative but coupled with a modest amount of experimental data can provide analytical expressions to problems not amenable to mathematical solution.

The procedures requires listing all of the parameters that are expected to influence the outcome of a physical interaction and identifying their fundamental dimensions. The parameters are then grouped into combinations such that the dimensions of the components cancel mathematically to leave a dimensionless ratio. Experiments are then used to find relations among the dimensionless ratios. The relations thus found are independent of the size of the system employed which allows the use of "scale models" for testing.

If a set of different sized "models" do not produce identical dimensionless results, the difference must be due to a parameter that has not been included in the scaling relation. The outcome of thoughtfully designed tests can reveal the magnitude and direction of the influence of any possible factor.

The factors included in the analysis of pneumatic tires and two dimensionless mobility groupings are shown in Figure 1. The results of tests in the soil bin revealed some significant relationships. The data showed that soil strength expressed in psi correlated to the test data well. However, the sand data could be correlated only if the soil parameter had dimensions of force over length cubed. This led to the use of the soil factor G, the cone index gradient, in psi/inch.

Other results were that tire deflection had more effect in the sand than the clay; that tire width was more significant than the diameter; bias ply and radial ply tires were closely similar in ability if they were geometrically similar (i.e. of the same size and had the same deflection), and velocity affected performance especially in the clay.

Some of the relations developed for tires in sand are shown in Figure 2. Similar relations are found for wheels on clay and for track systems. There is some scatter of data but refinements have been made by analyzing such deviations and modifying the basic dimensionless ratio. The current state of the system is described in a recent report by Turnage (MP GL-95-12).

Before taking a look at the deficiencies of the respective analysis methods, it is appropriate to recognize that the present system as incorporated in the NATO Reference Mobility Model is useful and has been applied successfully to many practical problems. There is no better recommendation than "It works" and both methods have records of successful applications. It would be nice though to

have more comparative results produced by neutral observers. Many would say that if it works leave it alone; striving for something better is not worth the trouble. However, the curious purist within me would like to understand how and why both work. So let me continue.

The cone index system uses the cone penetrometer to measure soil strength and the Waterways Experiment Station remolding test to measure the probable loss in strength due to repetitive traffic. Also one has to identify a critical layer. Cone index values have been demonstrated to be a good measure of strength for saturated or nearly saturated fine-grained soil. Cone index in this case represents the cohesion in a $\phi = 0$ soil. Test results clearly show that the result of the system is a good indicator of the performance of a vehicle. Furthermore, the relation, once derived, is the same for any soil. A certain cone index implies the same vehicle performance whatever the soil type.

If the soil is cohesionless, the cone index can be interpreted to yield a measure of the coefficient of internal friction ($\tan \phi$). No remolding index is required as such soils usually gain trafficability with additional traffic. Once more ample data support the usefulness of the system to predict vehicle behavior. The results are not as precise however. The relation is not quite the same for all cohesionless soils. Carefully controlled tests reveal that a certain cone index value will not necessarily yield equal vehicle performance in all soils. The difference is not huge and for most field work it is insignificant. This is an awkward but not devastating circumstance. Furthermore, the differences can be accounted for by an adjustment for the characteristics of the soil. I think it may even be possible to modify the cone slightly to take care of the variation.

There seems to be no way the simple cone penetrometer can be used to separate cohesion and friction in soils having both of these elements. For military applications this is a refinement that can easily be foregone. For other applications the short coming could seriously limit the usefulness of the cone index system. For example, in agriculture, work often occurs in c-ϕ soils and, there, efficiency is a prime factor. To calculate all the benefit of the soil's traction potential it probably is necessary to measure both factors. The only recourse I see is to adopt a separate shear test similar to the one used in the soil value system.

The best that can be said for the remolding test used in the cone index system is that such a test is necessary and this one works. However it is awkward, noisy, slow, and relatively complicated. Conceptually there are alternate methods that have more desirable characteristics but their effectiveness needs to be proven.

In the soil value system, the plate penetration test is cumbersome and slow. It was claimed to measure soils properties but, in fact it simply represents a plate penetration test.

Furthermore the data it provides can be misleading. In a layered soil, as most are in nature, two plates of different size can be measuring two different things (Figure 3). A small plate may not be influenced at all by a strong (or weak) layer while the larger one is. Even then, to represent a vehicle, the plate should be as large as the bearing width of the vehicle which is an impossibility. Furthermore, the plate averages the soil strength over a depth that may not be appropriate and it cannot probe to the full depth of interest. I think this test should be abandoned; it is useless and perhaps erroneous.

The in-situ ring shear test has much to recommend it but it is not without problems. Laboratory studies show that the soil does not remain confined within the loaded area but flows out from under. The soil may do the a similar thing under a tire or track but it is probably dependent on the size of the sheared area and not likely to be the same for a small ring as for a vehicle. I am aware of only a small amount of data that directly compares in-situ-ring shear data with triaxial data for the same soil conditions. These results show that the ring shear device does not yield the same friction angles as the undrained triaxial test. However, it is possible that the ring shear results are related to the shear under a traction element. This implies, though, that the ring shear test does not produce fundamental parameters but really is another index test. Some good test data are needed to establish the utility of the ring shear test.

The soil value system does not recognize the need for a remolding test. Available test data indicate that the residual shear value of the ring shear test does not adequately reflect the effect of remolding. A separate test could be developed - in fact it would seem that a test that provides a before and after ratio for the cone index system could be used in the soil value system also. Without such a test the usefulness of the system may be limited to certain soils and one-pass only.

So, in one case, the cone index system, we have a lot of good empirical data but no direct analytical procedure and in the other, the soil value system, we have an analytical procedure that uses suspect data and probably is of limited applicability. Yes, we can plug numbers into the computer and get answers back. And some of them look reasonable and, for those that don't, its possible to just tweak the input a bit to make it look better. But it seems to me that at some

point it will be necessary to better understand how traction is developed. How many engineering successes are achieved by analyses that do not use fundamental properties of the materials and for which the pattern of the mode of failure is only sketchily known? I believe that if someone listed a set of fundamental parameters like c and ϕ, and σ and ϵ, no one could use them to get a valid prediction of traction.

Figure 1

$$N_c = \frac{Cbd}{W} \cdot \left(\frac{\delta}{h}\right)^{1/2}$$

and

$$N_s = \frac{G(bd)^{3/2}}{W} \cdot \frac{\delta}{h}$$

where

N_c = clay-tire numeric
C = cone index (for cohesive soils, lb/in.^{2})
b = tire width (inflated, unloaded tire, in.)
d = tire diameter (inflated, unloaded tire, in.)
W = load on tire (lb)
δ = tire deflection (inflated, loaded tire, in.)
h = tire section height (inflated, unloaded tire, in.)
N_s = sand-tire numeric
G = gradient (slope) of the cone index versus depth curve (for frictional soils, lb/in.^{3})

Figure 2

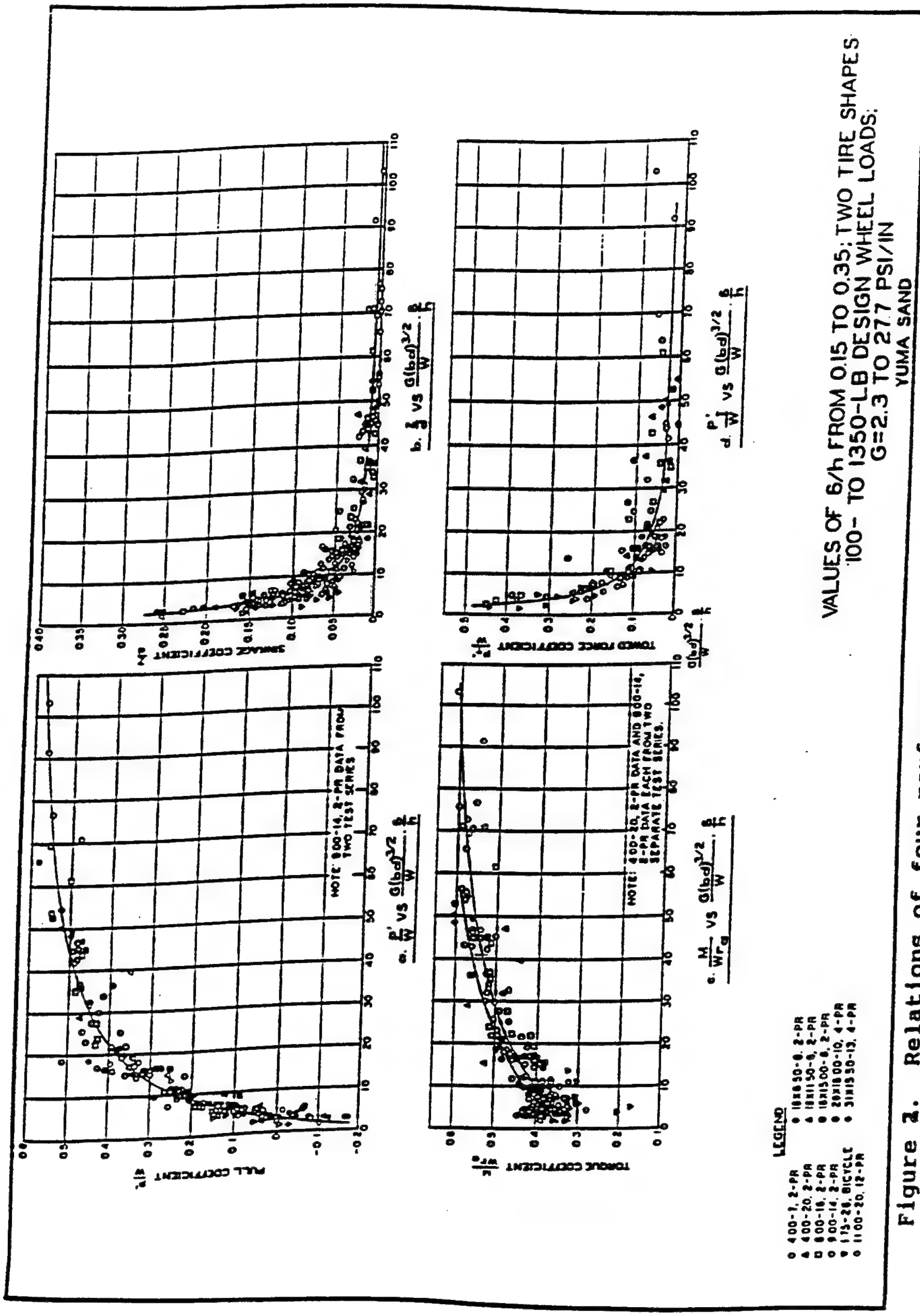
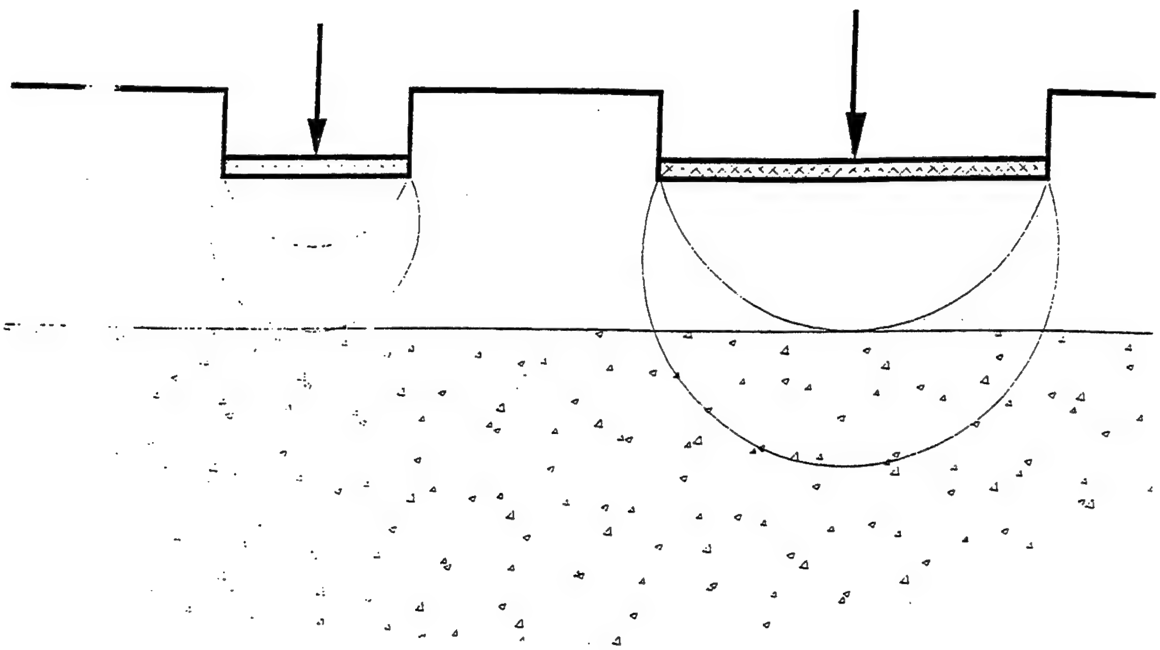


Figure 2. Relations of four performance coefficients to sand-tire numeric (from reference 2)

Figure 3.

Soil layers affect bearing values



The Origins and Development of Quantitative Terrain Evaluation*
WES Retired
Warren E. Grabau

My friend Newell Murphy asked me to present a brief synopsis of the origins and development of the concept of quantitative terrain description, as practiced at the Waterways Experiment Station, and from the special point of view of the cross-country mobility model. I was happy to oblige. I suspect that he chose me, not because I possess any intrinsic merit, but rather because I am probably the only survivor of the dim "days of the beginning" that he could conveniently lay his hands on. In any event, I propose to sketch out for you my memories of where the concepts came from, the basic philosophy behind them, and how those ideas developed over the course of time.

To properly understand the beginnings, a number of seemingly independent threads must be pulled together. Thus, some of the things I discuss at various stages of the story will sound like digressions. I can assure you that they are not; if you bear with me they will all eventually come together.

So let us go back to the dim days just following the Second World War. You will perhaps recall that many of the campaigns of that war were conducted in places where we had never dreamed of fighting. As a result, we were utterly unprepared to even exist, let alone fight savage campaigns, in such places as New Guinea, Guadalcanal, North Africa, the Aleutian Islands, and the Italian peninsula. It is hardly surprising that the post-war assessment of those campaigns revealed that the <u>environment</u> had, in one fashion or another, been responsible for the expenditure of far larger amounts of time, effort, manpower, and materiél than had been anticipated. One consequence of that realization was a growing determination that it should never happen again. We would do whatever was necessary to ensure that in future we would <u>know</u> what to expect in any of the various environments of the world, <u>and</u> that our weapons and other materiél would function properly in those places.

A number of steps were taken at that time by the Department of Defense, but only two are of peculiar interest to us. One of the first items of business was to make sure that our military equipment would function properly in "extreme"

environments, and to that end the US Army established three special "test stations," **(Fig. 1)** one at Yuma, AZ., which was intended to represent desert environments (remember North Africa?); another was located at Fort Sherman in the Panama Canal Zone, to deal with tropical environments (remember Guadalcanal and New Guinea?); and the third was located at Fort Wainwright in Alaska, to deal with arctic conditions. You may wonder why no temperate-zone test station was established. The reason is that we already had elaborate facilities at such places as Aberdeen Proving Ground, Fort Knox, Fort Belvoir, and others. And besides, we believed that we already understood pretty much everything that could happen to us in temperate zones! In retrospect, it seems a touching delusion. The general idea was that any new item of military materiél, or any new procedure, would be subjected to use tests at the three special test stations, and that those tests would reveal any flaws in design that would inhibit their utilization in similar environments anywhere in the world.

The second step of interest to us was the creation of a special research effort to determine why our military equipment had so often failed so dismally, and to develop criteria for design and utilization that would ameliorate the situation. In other words, the idea was to tell the designers precisely what kinds of environmental conditions the item of materiél would be likely to encounter, to enable them to design around those conditions. This step actually had several parts, but again only a few are of immediate relevance to our story. One of the things which was noted in the post-war assessments was that the military vehicles of which we were so very proud, such as tanks, weapons carriers, and even trucks of all types, tended to become immobilized with appalling frequency. In other words, our Army had not been nearly so mobile as we had thought it would be. You must understand that this perception was not the result of any kind of quantitative assessment; rather, it was entirely a product of anecdotal information. In any event, one consequence was that a new research effort was organized, the objective being to improve cross-country mobility. We are all here because of that decision. One portion of that effort was located here at WES, where it was known simply as "the mobility program." Other major components of that effort were located elsewhere, and all were relatively lavishly funded.

The second portion of the research effort that concerns us here had an impressively grandiose title. It was called the Military Evaluation of Geographic Areas, which, of course, in accordance with time-honored military practice, was immediately converted to the obvious acronym: the MEGA project. The acronym did not refer to the size of the project! It was located at WES, because, I suppose, the Corps of Engineers was responsible for providing terrain intelligence to the field forces, and one objective of the MEGA project was clearly to enhance terrain intelligence.

When I arrived on the scene in 1956, the project had a staff of three: Joseph Compton (the section chief and director), a secretary, and Robert Turner (a civil engineer). With my arrival, the manpower was increased to four. We four were supposed to determine, in quantitative terms, the interactions among the various world environments and military men, materiél, and activities. Think about that for a moment! We had no shadow of a clue as to how to go about the task. You must understand the context. Both Joe Compton and Bob Turner were civil engineers with special experience in soil mechanics, and I was a geologist and physical geographer--technically, a geomorphologist. I suspect that I was thrust into the group because I had spent several years working on the National Intelligence Survey (NIS) project for the Military Geology Branch of the U.S. Geological Survey. The NISs were country-by-country descriptions of geography, geology, hydrology, climate, and so on; that is, they were environmental descriptions of selected regions of the world. The conceptual connection between the NISs and the objectives of the MEGA project are obvious.

However, all of us NIS types had been trained in our various disciplines in absolutely classical fashion, and the importance of that fact cannot be overemphasized. For example, each NIS folio had a map devoted to terrain features, and the mapping units were nothing more than those of a classical geomorphological map. That meant that landforms, like floodplains, cuestas, badlands, fold mountains, river terraces, or whatever, were identified. Why was this mode chosen? Well, because we had all been trained to recognize terrain features in terms of their origin. Aside from the obvious fact that we didn't know how to do anything else, I suppose the assumption was that since all floodplains

had formed in basically the same way, they would all have the same properties. We simply knew that mapping features of common origin resulted in a map which also defined their geometries and compositions, within very narrow limits. This was revered wisdom, and none of us were prepared to challenge it.

Vegetation cover was very much the same; the NIS map units were borrowed straight out of classical plant geography texts, and included such categories as "mid-latitude deciduous forests," "boreal forests," "sub-tropical monsoon scrub," and "prairie." As well as, of course, such really useful terms as "cultivated areas." It was simply an article of faith that one could "translate" those terms into information that would allow us to estimate the effect of that vegetation structure on all manner of military affairs. It is my impression that the designers of the NIS format never considered them as useful in a tactical mode; their focus was almost entirely strategic. That is, they were not envisioned as making it possible to estimate, say, the effectiveness of an artillery round, or the movement of an individual vehicle.

To be sure there were small, nagging doubts about the NIS format, but only as to whether the classification systems were adequate. Thus we spent a very large amount of time trying to improve and refine the classifications. "Tropical evergreen forests" were subdivided into "two-layer" and "three-layer" forests, and so on. We were mentally locked into the straitjacket of our academic training.

About 1955 some of the people who had fought in North Africa had noticed that some of the North African deserts seemed to have features and characteristics that did not seem to be in evidence at the Desert Test Station at Yuma, and that led to the suspicion that Yuma did not truly represent "world deserts" as well as it was supposed to. Such questions eventually reached such a pitch that WES was requested to conduct an evaluation of the Yuma test station, to determine whether it was `analogous' to the other desert regions of the world which it was supposed to represent. Thus was born the Desert Terrain Analogs Study (DTAS), which eventually proved to be the hammer that broke through our mind-set.

By the time I arrived on the scene in 1956, the DTAS was well along. It had been turned over to the WES Geology Branch, and Charles Kolb, John

Shamburger, and Will Dornbusch were among the principle players. The first question was: How does one compare two landscapes, such as that of the Yuma Test Station and the Takla Makan of Central Asia? In other words, what is a terrain analog? Given our classical geological and civil engineering training, the answer was pretty obvious; we would simply map landforms, soil types, and vegetation structures. If those three sets of criteria matched, then the two landscapes were analogous. For example, if alluvial aprons were found in both Yuma and the Takla Makan, and the soil types of those features were similar, and both areas had strips of xerophytic vegetation growing along the washes, then the two areas would be analogs of each other. Simple enough, right?

And indeed that is exactly what Charlie Kolb and his group started out to do. The assumption being that a landform type in one place is going to be the same as that same landform type in all others. You will immediately recognize that this is precisely the basis for the NIS studies, and therefore, I felt right at home. However, Charlie Kolb and his crew took the injunction to establish quantitative relationships between military stuff and the terrain very seriously. They decided to provide as much quantitative data on the environment as possible. The assumption was, quite correctly, of course, that we needed to provide information which would make it possible to evaluate the operability and effectiveness of military materiél, and we were chauvinistic enough to believe that mere engineers, like the people who tested materiél, would need help in translating a landform term, like alluvial fan, into numerical data, like surface slope angle. But this raised a small problem. What kinds of data did the test and evaluation engineers need?

It came as something of a shock to discover that neither we nor the test and evaluation people knew what kind of data would be useful! We spent a lot of time trying to visualize what properties of the environment would effect the behaviors of such things as tanks, trucks, artillery shells, machine guns, and so on. For example, since it was pretty obvious that a very rough and broken terrain provided more protection from a bursting artillery shell than did a perfectly smooth topographic surface, some information on the configuration of the topography would be nice. Information on soil types would obviously be a good thing because vehicles of all types reacted to soil properties. The effectiveness

of small-arms fire would clearly be a function of the numbers and of sizes of trees.

As a result of this kind of brain-storming, we arrived at a very crude idea of what we thought it would be nice to have. At this point we were sure that we had the problem solved, because we could map the extent and distribution of landforms, and we knew that all landforms of similar origin had similar characteristics. Determine one, and we have determined them all. It was very simple.

It is important at this point to note that the thrust to provide quantitative terrain descriptors was not to provide numerical inputs to mathematical simulation models of materiél performance. This is for the very simple reason that not only were there no such things, but they had not even been imagined! Instead, we were trying to provide information such that the test and evaluation people could: 1) design useful test procedures; 2) ensure that such tests could always be performed under the same conditions; and 3) ensure that the test results could be reliably related to other parts of the world.

There was one nasty little residual problem stemming from the fact that the geographic data on the various regions of the world, such as Lop Nor and the Empty Quarter, were a little sparse. Furthermore, virtually all of the little information that was available for such areas had been collected by people with classical scientific or engineering educations, and thus it was all classical stuff. We did not appreciate exactly what that meant, because we still believed that a landform was a landform. These considerations forced some compromises, but eventually we arrived at a series of attributes of the landscape that we thought we could map with enough precision and accuracy to make it worthwhile. I like to think that the term "terrain factors" was coined because we were thinking of each landform as an entity like an equation. We were simply isolating the component parts of the landform like a mathematician "factors" an equation. However, I have an uncomfortable feeling that there was nothing so logical as all that behind it. In any event, it turned out to be a fortunate choice of terminology, as will be seen later. The terrain factors finally selected are listed in **Fig. 2**. The results were, of course, to be presented as a series of maps showing the geographic distributions of the various factor classes.

It must be remembered at this point that we still intended to map the factors by simply deriving them directly from landforms. That is, we still assumed that there was a direct equivalence between a landform and a specific and very narrow range of terrain factors. By this time a very few of us had concluded that a terrain factor was an attribute of the landscape that could be defined by a single quantitative measurement, and had begun to use it more or less consistently in that restricted sense. Thus local relief was a factor, because a single measurement could be used to characterize the vertical distance from an interfluve to an adjacent drainage channel, but soil type was not, because one could not characterize all of the useful properties of a soil with a single value. Given these definitions, it should be noted that the "factors" used in the DTAS were not all true factors! Instead, they were a mish-mash of factors (i.e., attributes defined by a single measurable value) and subjectively-recognized classes, such as the "characteristic plan" category. Some of us were vaguely troubled by this, but we simply didn't know what else to do!

At this point in time Charlie Kolb and his people did a very intelligent thing. In order to maximize the information content of the maps, they decided to include a tabulation of landforms with a little graph showing the ranges of the various factor values exhibited by each landform (**Fig. 3**). We fully expected this to be a relatively trivial task, because we were all entirely confident that each landform, such as an alluvial apron, would exhibit a very narrow range of values for each factor. We were, to put it mildly, naive! When we actually tabulated those values objectively, using data from the relatively few places in the world where such details could be reliably obtained, we found the situation as illustrated in **Figure 3**. It is quite clear that the tabulation of ranges, as actually measured, is so great that the primary purpose of the tabulation was to serve notice on the user of the maps that he should not use landforms as a direct and reliable source of terrain factor data!

This was not at all what we had in mind when we started the exercise, but it taught us a profound lesson. It is, unfortunately, a lesson which has not yet penetrated the academic literature on geomorphology and geology. Even modern university texts cling to the notion that each landform is distinguished by a narrow range of parameters defining its shape and properties.

One side-effect of the discovery was that it enormously magnified the task of mapping the terrain factors. The final reports took much longer to compile than we had originally scheduled. In the final version, analogous terrains are those which exhibit the same array of factor value classes. The resultant folios are dramatic, and utterly unlike anything previously produced. They are called "Analogs of Yuma Terrain in (various world) Deserts. The WES library has a complete set, and they are well worth viewing.

But what were they, actually? It took us a long time--years, in fact--to realize what we had done. We had demonstrated that it was possible, first, to describe the attributes of the landscape in terms of measurable parameters that could be used as design criteria, and second, to map the spatial distributions of such parameters. If you reflect on this for a moment, you will realize that we had cracked opened the doors to what amounted to two new worlds, namely the mathematical simulation model that uses terrain data as input, and the geographic information system, which is required to provide environmental data for such models! But please do not be under any illusion that we understood this at the time! Remember, this was in 1958, at a time when the only computers were still made with vacuum tubes, and used primarily for designing atom bombs and compiling actuarial statistics. The notion of a structure like the present off-road mobility model was still some distance in the future.

Nevertheless, it was clear that we could now discriminate much more finely among what we might call terrain types than we had ever been able to do before. For example, when we applied our new-found expertise to the huge alluvial aprons at Yuma, we found that we could subdivide them into much smaller units which displayed highly consistent internal homogeneity. There were doubters, and some of them were in high places. This lead the MEGA project people to design an experiment to demonstrate that these new terrain units were real, in the sense that they would effect the performance of military materiël. The items of materiël easiest to obtain were a 3/4-ton truck and a jeep. Across the alluvial aprons at the Yuma Test Station, we laid out a number of test traverses designed to cross a number of our new terrain units, which had been defined solely in terms of factors similar to those used in the DTAS. Alluvial fans are in general highly trafficable, and we exploited that property by designing the traverses to

minimize every possible effect of soil strength. What we wanted was to determine whether such things as slope, local relief, and so on would also effect performance. The idea was to run the vehicles along these traverses while carefully monitoring time-made-good and fuel consumption.

Oddly enough, we had internal opposition. We were told in no uncertain terms that cross-country mobility was none of our business, and furthermore that we would screw it up and thus give the "true" mobility program bad press. Therefore, we should not be permitted to conduct the experiment. We eventually saved our own skin as well as the experiment by arguing that we were not really conducting a mobility experiment. We were instead using the vehicles as instruments to measure the properties of the terrain. That we actually got away with it is still a source of amazement to me.

When the data were all tabulated, we found to our joy that significant differences in performance had been imposed by terrain variations. We could clearly "see" the terrain types in the performance data. As we meditated on the implications of the experiment, we began to appreciate that we had a very primitive form of predictive capability. That is, we could predict performance by careful description of the terrain. It was a long way from being a predictive model in the modern sense, of course, because it was entirely empirical. One had to run the vehicle over a sample terrain in order to get a measure of performance, from which one could presumably "predict" what the vehicle would do on all "analogous" terrains.

It was at about this time that the true meaning of the MEGA project objective--to determine in quantitative terms the interactions among world environments and military men, materiél, and activities--began to dawn on us. We had to be able to predict performance for everything, everywhere in the world! As we reflected on this, we began to understand that there were only two fundamental ways in which that could be done **(Fig. 4)**. We could develop empirical models, such as the one we could envision from the tests at Yuma that we had just completed, or we could develop what we tended to think of as analytical models. Ideally, the latter would operate on the basis of first principles. For example, a suspension system model would track the actual motion of the components, such as wheels, springs, shock absorbers, and so on,

as the vehicle moved across an irregular surface. One could envision such a model as an equation, or more likely a set of linked equations, that accepted a topographic profile, defined as a set of x-y coordinates, as a forcing function, the physical and dynamic characteristics of the suspension system as the operational agent, and the output as vehicle hull motion. You must understand that we had not the foggiest notion as to how to go about formulating such a set of models, but it seemed clear to some of us that it was at least theoretically possible. Of course, hybrid models, partly empirical and partly analytical, were also possible, and in fact, as events worked out, that is the configuration of the current NRMM.

In the meantime, it was very clear that such a model would require exquisitely accurate and detailed terrain descriptions. This was a daunting prospect, because we had a very limited capability for acquiring such data. Indeed, in most cases we simply did not know what terrain factors we would have to measure. For example, what terrain factors--and remember the restricted definition of the term "terrain factor"--actually interacted in significant ways with a moving vehicle?

Determining what attributes of the environment--what factors, in other words--imposed constraints on the performance of all items of materiel, whether weapons, vehicles, or whatever, was a major problem. We were striking out into new territory, and it was all pretty mysterious. It seemed logical at the time that we should be able to extract some useful insight into such matters from an examination of the historical record. For example, the after-action reports of World War II were known to contain comments on the reasons why certain operations ran into trouble. If those records were carefully examined, we ought to be able to compile not only a body of statistics which would tell us what kinds of effects were most troublesome, but also what environmental factors had created the problems. Thus was launched the Historical Records Study, in the course of which literally thousands of records of incidents during World War II were tabulated and analyzed.

It all sounded so logical! But as time went on, we discovered that the concept had serious flaws. We expected to find many items related to mobility, and indeed that turned out to be the case. Again and again the records contained accounts of operations coming to grief because vehicles got stuck in the mud,

even in the North African Desert! But not once did the accounts mention why or how! Even so, the "stuck in the mud" statistic reinforced a conviction already deeply embedded in the minds of the people managing the mobility program. The problem of cross-country mobility was that of trafficability, that is, of soil-vehicle interactions.

Curiously, rarely if ever did the historical records mention any other kind of immobilization, such as being brought to a stop by a cut bank, or whatever. There were those of us who began to have doubts about the nature of the statistics we were obtaining, because it seemed beyond reason that the only thing that could bring a vehicle to a stop was getting stuck in a mud-hole. At that time people who had actually fought in the various theaters were still pretty common, and so a few of us, very much on the QT, looked up a few tank- and truck-drivers and asked them about their own experiences. What we found was that they got stuck in the mud, rightly enough, but all too frequently it had happened because they had been forced to take a path across a muddy field because the Germans had blown a hole in the road, and their vehicles could not cope with the geometry of the crater. In the desert, they sometimes hunted for miles up and down a wadi until they found a bank that had a configuration that their vehicles could manage. In other words, more often than not they got stuck because they were forced by geometric obstacles of various kinds into using routes they would not otherwise have chosen. Asked if they would have been able to do better if their vehicles had better obstacle-surmounting capability, their reply was nearly always a heartfelt affirmative.

This at least confirmed what we had believed intuitively, that obstacles of various kinds were very real inhibitions to cross-country mobility, and that no amount of single-minded concentration on trafficability would entirely solve the mobility problem. But it still did not tell us exactly what terrain factors actually interacted with the various kinds of vehicles. We had gained a conviction that a terrain description for mobility purposes would have to include obstacle data of various kinds, but we still did not know exactly what they were. Do not think that we did not theorize. We did. And as it eventually transpired, our conjectures turned out to be not far off the mark. We actually built some scale models of commonly-used military vehicles, ran them over scale-model

topographies, and of course discovered exactly what you would expect (**Fig. 5**). We explored the properties of approach and departure angles, crested obstacles on which wheeled vehicles "hung up," side-slope stability, and so on. From this we devised techniques for measuring and describing actual topographic surfaces. However, there was no immediate prospect of organizing a program to test the responses of prototype vehicles because the formal mobility program was still devoting very nearly all of its funds to the soil-vehicle interaction problem, i.e., to trafficability.

The Historical Records Study also examined after-action reports from the South Pacific Theater, but they were even more ambiguous than those from the European and African theaters. However, participants told us vehicles had tended to stay strictly on trails, because it was "too difficult" to move through the "jungle." No one seemed to be quite sure why that was so, but it was pretty universally agreed to be true. Our conjecture was that two effects were responsible. First, the trees were usually so big as to constitute impassable obstacles and even heavy vehicles had to follow very tortuous paths in order to avoid them. Second, in a true jungle--and there were lots of those in the South Pacific--the visibility would be so limited that speed would fall to near-zero. This led to the conclusion that we really ought to understand how vegetation structures were put together.

By this time we were beginning to develop a healthy cynicism about the existing classification systems, because we had begun to look at vegetation types with new eyes. Right here at Vicksburg we are completely surrounded by a deciduous forest, and even a casual examination revealed there were parts of that forest that were open and clear at ground level, as if one were in a cathedral, while other parts had such dense understory plants that one could barely see one's hand in front of one's face. Yet both of these physiognomies were classified by plant geographers--and foresters--in the same way! It was very clear that we had to have something better.

An extended look at the available botanical and forestry literature gave us virtually nothing that was useful. So we set out to develop our own descriptive system. There were many reasons other than mobility for studying the physiognomy of vegetation. Our investigations were far more comprehensive

than would have been the case had mobility been the only consideration. In fact, we looked at vegetation assemblages from crown to root, and developed some rather ingenious techniques for establishing the three-dimensional geometrics of plant assemblages. We even built a laser range-finder long before such an instrument was available on the commercial market. We used it to locate in three-dimensional space the positions of branch bifurcations in forest canopies far overhead. Why? Because we wanted to know where an artillery shell or an anti-personnel bomb equipped with a contact fuze would explode as it came plunging downward.

From the point of view of mobility, it was very clear from early on that stem diameters were a critical factor. For each vehicle category, stems below some critical diameter could be over-ridden, which would slow the vehicle but not stop it, while those trees with trunk diameters beyond the critical value constituted obstacles which would have to be avoided. In other words, the denser the forest the more circuitous the route, and therefore the slower the speed-made-good. That automatically meant that stem spacing was an important factor.

The Mississippi floodplain has some large, nicely-flat areas covered with willow forests of various ages. By careful selection, we were able to find a whole spectrum of stem sizes and spacings, in which we conducted full-scale vehicle tests to determine which spacings could be negotiated. At this point in time we defined stem spacing as the modal nearest-neighbor distance. One obtains the number by selecting a large number of trees at random, measuring the distance to their nearest neighbor, and then calculating the modal value. It was a technique borrowed straight out of the forestry manuals, and was accepted as revered wisdom.

As most of you know, tests using prototype vehicles are pretty expensive, so we looked around for a cheaper way to get useful numbers. We had model vehicles, so why not model forests? Nothing could be simpler. We would create our forests out of a big sheet of plywood with zillions of holes drilled into it on a regular grid pattern. At this point we assumed, as had every botanist and forester in the world, apparently, that the actual stem distribution in a forest is random. In this context, `random' means that a tree is as likely to be at any specific place as at any other. We cut a lot of little pegs from dowel rods, and inserted them

into our plywood base according to a random-positioning algorithm. It was simple and straight-forward, because we could change the stem spacing by the simple expedient of adding more members to the population. We then ran our model vehicles, which had been built with steering characteristics to mimic the prototypes, through our model forests. The very first thing we did, just to be sure our calibrations were correct, was to duplicate the prototype tests which we had run in the willow stands. And guess what? Our model vehicles were easily able to penetrate model forests exhibiting the same number of stems per unit area as those that had brought the prototype vehicles to a stop! It took us nearly two years to figure out why.

To make a long story short, a very clever professor of Botany at Marshall University, Dr. Howard Mills, finally discovered that trees in a forest are not randomly positioned, as every botanist since the beginning of Time had assumed. They are instead positioned in a remarkably ordered way. He called it a `randomized hexagonal array.' **(Fig. 6)** Imagine that the area is `tiled' with regular hexagons. There is only one tree stem on each hexagon, and the most likely position of that stem is near the center of its hexagon. Of course the stem can occur at other positions within the hexagon, but the probability of that happening drops with increased distance from the center. In other words, most trees are located near the centers of their hexagons, and only a very few will be near the edges. Nature is not quite so geometrically precise as my explanation suggests, but it comes astonishingly close!

We built some model forests using the `Mills rule,` and were able to replicate prototype-scale test results with models without difficulty. Even so, the reason is not obvious. It is because true random arrays, such as our original model forest, invariably result in relatively large stem-free openings here and there, with other areas exhibiting very dense clumps. A vehicle driver can usually avoid the dense clumps and find a path from opening to opening. On the other hand, Mills' randomized hexagonal arrays have a relatively uniform distribution of stem locations. There are no openings or dense clusters. Real forests obey the Mills rule, not the random rule!

Dr. Mills also discovered that the laborious nearest-neighbor sampling procedure did not provide a useful measure of stem spacing, and proposed an

alternate scheme. It was astonishingly simple: Swing an imaginary circle enclosing exactly 20 stems around any arbitrary point. The area of the 20-member circle divided by 20 gave us the `occupance area' of each stem, and if that area is treated as a circle, the diameter of the `occupance area' circle correlates very closely with the ability of a vehicle to move through the stand. Whereas, as we have seen, modal nearest-neighbor stem spacing measured in the traditional way does not. We tested it from one end of the planet to the other, and it worked every time. It was not only much faster and easier than the traditional `nearest neighbor' method, but we also found that we could get reasonably reliable estimates even from airphotos. Result: We had a very neat method of acquiring two critical factors, namely stem diameters and stem spacing. This enormously simplified the data acquisition problem.

The same two factors were useful in determining over-ride characteristics, but they did not solve the whole problem, because some experimentation in the field quickly revealed that the wood of some species is a lot harder to bend over or break than others. Thus, a truly complete method of predicting the force required to over-ride a specific stand of trees or scrub required a strength factor. It turned out that bending stress correlated pretty well with species, at least in temperate zone vegetation stands. We were able to acquire the needed value by establishing the species, which is a relatively easy thing to do because botanists have been doing that since the beginning of the world.

Visibility was another matter entirely, and despite some rather intensive experimentation, we were never able to develop any simple or reliable method of <u>measuring</u> it, let alone a method of describing vegetation in such a way that it could be calculated. My own suspicion is that visibility is so subjective that one would have to devise a separate set of rules for each individual.

In any event, we now had identified the major vegetation-related factors that influence mobility, and had even developed means of acquiring those numbers from actual vegetation stands. We were thus in a position to establish empirical relations between vegetation stands and vehicles, even if we had no deterministic computational models that predicted them. Furthermore, we could even map the distributions of classes of those factors with some facility, so we could produce rather elegant vegetation factor maps for mobility analysis.

During most of this time the Viet Nam War had been grinding along, and it had become apparent to many people in high places that the Armed Forces knew relatively little about how to cope with many of the environmental conditions they were encountering. Thus it was that the Advanced Research Projects Agency (ARPA) approached WES with a proposal that WES establish the mobility conditions of Southeast Asia, and that Thailand be used as the test area. We could be assured of the full cooperation of the American military mission in Thailand, as well as that of the Thai Government. Very few constraints were imposed, and we were encouraged to design our own procedures and objectives. The only requirement was that at the end of the day WES should be in a position to advise the Armed Forces as to what they could expect in the way of mobility conditions in that vast region. It was like being presented with the keys to Eden.

By this time computers had developed to the point where they could be used as standard tools in scientific and engineering contexts. A very few of us had realized that it was therefore theoretically possible to develop a deterministic mathematical model that would be capable of predicting the performance of a military vehicle going across country, if only we could figure out how to put all the parts together. So we theorized **(Fig. 7)**. To be sure it would require enormous computational power, but we believed that problem would be tractable with computers. Perhaps not today, but computers were bound to improve. Rather than conduct the classical mobility study with emphasis on soil-vehicle interactions, a little clique at WES conned the management both in Vicksburg and in Washington into accepting the notion that we use ARPA's money to develop such a <u>mobility</u> model, using the whole country of Thailand as a test range! To our considerable surprise and almost inexpressible joy, ARPA accepted our proposal as written. Thus was born MERS, the Mobility Environmental Research Study.

In Thailand over the next two years, we used everything about terrain description that we had previously learned, and used the collected data to select and describe a number of vehicle test sites. One of the several things that became clear as a consequence of the test program was that there were at least two distinct kinds of effects created by surface irregularities.

There was, first of all, the well-known, albeit largely undefined, obstacle effect, in which the surface geometry features were large enough to actually act as an obstacle to the passage of the vehicle. Thailand abounded in such forms, including the ubiquitous rice-field bunds or dikes, **(Fig. 8)** sometimes in combination with small ditches and canals. Even in those cases where the feature could be readily surmounted, an impact at high speed could throw the vehicle out of control, or wreck the running gear. The second form of microrelief was much more subtle, and it consisted of such small-scale irregularities as to impose no direct impedance to the passage of a vehicle. However, we discovered that even very small features, on the order of a few centimeters in height, if properly spaced, could so excite the suspension system that the vehicle was soon thrown out of control, or forced to pitch, roll, and/or yaw so violently that the driver could no longer tolerate the motion. Sometimes the effect became a problem only after several minutes of driving, after which the accumulated stress of the violent vehicle motions became physically so painful to the driver that he would reduce speed to ameliorate the effect.

Again Thailand abounded in such microrelief expressions. A notable example was quite unexpected. During the dry season, the clay-rich soils of the rice fields dry to concrete-like consistency, preserving the irregularities caused by the innumerable passages of water buffalo and farmers through the soft soil of the flooded fields. After the rice was harvested, the fields quickly developed a cover of grass, and were then invariably used for pastures. The buffalo and cattle kept the grass neatly trimmed, and from a distance the fields looked almost lawn-like. But the grass concealed a highly irregular surface with a relief of only five to 10 centimeters, and with a characteristic `wavelength' of 20 to 80 centimeters. It was quite amazing what some of those surfaces could do to the suspension systems of a military wheeled vehicle!

In any event, we were eventually forced to develop very rapid methods of measuring the cross-sectional profiles of such surfaces, for use as forcing functions for mathematical simulations of vehicle running gears. Surfaces of this general type--that is, those whose primary effect was to activate the vehicle's dynamic responses--came to be recognized as major players among the terrain factor complexes responsible for inhibiting the speed of cross-country vehicles.

By the end of the MERS project, we had in being a working mathematical simulation model that would predict with considerable reliability the speed and dynamic response performances of standard military vehicles on cross-country traverses. To be sure, it was very primitive and very limited, but it did what had never been done before. We could predict the cross-country speed of a vehicle with considerable reliability without actually running the machine over the ground! And equally important, we knew how to describe terrain in the quantitative terms required to drive the model. We knew the model could be fine-tuned forever, but we also knew that the first critical step had been successfully taken. It was a good feeling.

Having now followed, however briefly and incompletely, the chain of events and concepts that led eventually to the present NATO Reference Mobility Model (NRMM), let us turn back to the primitive factor maps that were created for the Analogs of Yuma Terrain folios, and follow their development to the present time.

I have no idea how matters now stand, but in the early days of the mobility modeling effort, there was always tension--and I think misunderstanding--between two schools of thought for using the same basic capability **(Fig. 9)**. As originally envisioned, the cross-country mobility model (CCMM) was intended simply to track the performance of a single vehicle over a very small piece of terrain that had been defined in exquisite detail. The objective was to develop a tool that could be used to evaluate the performance of individual and specific vehicles. We dreamed of a model so good that it could be used to compare the performances of vehicles while they were still on the drawing boards, enormously simplifying the development process. Ideally, that same model could be used to compare the performances of vehicles, or to predict the performance of a specific vehicle, in terrain situations on the other side of the world, without the need to ship the vehicle over there and actually run it on the ground. We thought of it as a design and evaluation tool.

Assuming this utilization, the relatively high cost of providing the enormously detailed terrain descriptions was largely immaterial. For example, acquiring the centimeter-by-centimeter microgeometry profiles required to appropriately exercise suspension system component of the model was very

time-consuming and costly, but because one would need only a limited number of such data sets, we could afford to spend the necessary time and money. After all, we would be able to use the same data again and again, for any vehicle that came down the design and development pathway.

Of course there were skeptics, and they had a point. Any designer worth his salt could look at the detailed terrain data of what might be called synthetic test courses, and specifically fine-tune a design to perform well on it. If you think this is unlikely, I will remind you that there were a lot of people--and probably still are--who believed that the vehicles which we used during and immediately after World War II were specifically designed to perform well on the test ranges at Aberdeen Proving Ground. Never mind what they did on the battlefield. They were selected on the basis of their performances on the test courses at Aberdeen! The very same process could operate with mathematical models as the evaluation tools!

Interestingly enough, there was a way to beat that problem. Once one knew the ground-rules, and had a large sample of detailed terrain descriptions acquired in various parts of the world, one could design an infinite number of synthetic "test courses," each unique in itself, but each "analogous" to a specific world terrain. We even developed a method of generating such "synthalagous" terrains, just to prove that it could be done!

As we have seen, a mobility model could also be used in a tactical sense. For this utilization, one would ideally require a somewhat simplified model, because one would mostly want to use it in a near-real-time mode, and that implied minimization of computational times. But even more importantly, one would require that large areas of the world be mapped in terms of the environmental factors required to drive the model. While this was obviously theoretically possible, the practical difficulties were immense. That is the primary reason why we made no attempt to map Thailand in such terms as a product of the MERS program. At that point in time, we believed it to be impractical. The secondary reason, which was somewhat sneaky and dishonest, was that we wanted to focus on the development of a very refined and elegant model for use as a vehicle design and evaluation tool. Rightly or wrongly, we believed that we ought to have a very elegant model first, after which we could simplify it for

tactical purposes, when and if a demand arose. In effect, we did not want the research effort diverted into the obvious tactical utilization channel until we fully understood the theory and practice of the modeling idea.

Nevertheless, it was obvious that eventually the model would be used in a tactical mode, and a measure of effort was devoted to the problem of providing such a model with terrain data. The problems were daunting. In fact, it is hard to know where to begin. I suppose the best way is to follow the King of Heart's advice to the White Rabbit: "Begin at the beginning..."

First, much of what I say in the following discussion will be a painful elaboration of the obvious to most, if not all, of you. I can only say that when the process started, about 35 years ago, most of it was not at all obvious to us. What I am going to do is to attempt to trace the history of the development of the GIS concept, including that of the various sub-elements of which it is composed.

When we first began thinking about a set of maps of terrain factors as a data source for any kind of analytical routine, our thought processes went something like this: First, **(Fig. 10)** we concluded that an individual analysis would be concerned with a single small unit of territory at a time. For example, let us assume that we had achieved Nirvana and actually had a vehicle performance model. In that case, the unit of examination would be a piece of landscape perhaps slightly larger than that which the vehicle occupied at any one time. For the sake of argument, say an area of 10 by 10 meters. That <u>unit area</u> (and that's the term we used) would be described by an array of numbers, each of which represented a factor value. One could visualize the terrain description of the unit area as a stack of poker chips, each with a number written on it. The analytical routine would "read" the number on the top chip, then the number on the second, and so on. When the vehicle moved to the adjacent unit area, the analytical procedure would read the stack of chips describing that unit area, and so on. Suddenly the fact that we had called the terrain attributes "factors" seemed fortuitous, because in effect, each number could be thought of as representing an input value, or "factor," in an equation.

This concept had several immediate implications. First, it implied that the maps would consist of an ordered array of unit areas, which was an almost-perfect analog of the <u>pixels</u> which formed scanner-obtained imagery. As

we had worked extensively with such imagery, this put us on solid and familiar ground. In our minds, pixel and unit area quickly became synonymous. On this basis, each pixel would be represented by a specific array of factor values. It was thus easy to visualize a set of factor maps stacked one atop the others, but with all of their pixels in perfect registry. In fact, it was no great stretch of the imagination to visualize the Analogs of Yuma Terrain maps in exactly that way.

However, the second implication was not so comfortable. Even on a 1:50,000-scale map, there are a lot of 10-meter pixels! It didn't take us long to realize that a 10-meter pixel at that scale was represented on the map by a square 0.2 mm on a side. In other words, scale limitations would defeat us if we tried to compile a set of factor maps of a region at any reasonable scale, because there was no way in which we would be able to label each pixel with a set of absolute factor values. We couldn't acquire the data, and we couldn't store it even if we got it--more about both these problems in a moment. That meant that we would have to label patches, each of which could be thought of as consisting of an aggregate of pixels. **(Fig. 11)** However, we would have to label those patches in classes of factor values **(Fig. 12)**, because normal terrain variability would ensure that no patch consisting of several pixels would exhibit exactly the same set of absolute values throughout.

As previously mentioned, data acquisition was regarded as a major problem. Suppose that one is interested in mapping an area of 2,500 square kilometers, which is really quite modest when one thinks of the areas covered by a modern military campaign. In that area, assuming a 10 x 10 meter unit area, there are 25,000,000 unit areas. Actually measuring the values of even a modest number of terrain factors of that many unit areas is manifestly impractical. In fact, the only practical method is to map relatively large areas, each of which incorporates a large number of unit areas, in terms of factor value classes.

For example, one can map the distribution of USCS soil types with reasonable reliability from air photos, given a modest amount of ground truth data. Since a USCS soil type is itself a class, if one was interested in mapping the precise percentage of sand in the soils of an area, one could actually get no closer than the range of sand percentage specified by the USCS classification

system. Thus, practical considerations of data collection forces the use of classes, whether one likes it or not!

These two attributes of the concept immediately raised the question of class subdivision. Each factor is represented in nature by a range of values. For example, using topographic slope as a factor, it is evident that the topographic surface may display slopes ranging from 0° to 90°. If the unit areas are small enough, it would be theoretically possible to label each one with a close approximation of the "true" absolute value, but if we must label an aggregate of pixels, the resultant patch will necessarily display a range of values. Continuing with slope as an example, there are theoretically three ways of establishing factor value classes.

First, one can use an arbitrary numerical scale, like 0-2°, 2-4°, 4-8°, and so on. This at least has the merit of simplicity.

Second, one can look for "naturalistic" breaks or discontinuities. In the case of slopes, certain dynamic processes involved in erosion and deposition results in very few slopes in the range from about 8° to 30°, and one could presumably use that discontinuity as a `break' between classes. Unfortunately, as it turns out, there seem to be very few such naturalistic breaks in nature, and thus it is not a very useful procedure.

Third, one can look at the model one is trying to feed, and use classes based on the amounts of error or ambiguity one is willing to see introduced into the computational process. Because we were thinking in terms of deterministic models, we assumed that the models would require absolute values. Obviously a computation performed with values at the upper and lower limits of a class might well yield quite different results, and therefore the computational product would, at best, be an approximation. The obvious thing to do would be to keep the classes as small as possible given the data acquisition and mapping difficulties.

Still another problem posed by this procedure is that the class breaks are model-constrained. One cannot create a multi-purpose factor map. Class breaks acceptable to a vehicle performance prediction model might be completely unacceptable to one for predicting the performance of anti-personnel artillery fire, for example. This is one of the several reasons why I still look with jaundiced eye on GIS systems which are pedaled as general-purpose. One

cannot serve many masters. We realized, of course, that the Analogs of Yuma Terrain maps were, even at best, a prime example of that flaw. Fortunately, the realization occurred several years after their completion, so we were able to chalk it all up to inexperience.

The problem of map registry reared its head very early. This is a whole mare's-nest of problems too numerous and too complex to discuss here in detail. In principle the whole problem could be avoided (or at least very nearly so) by collecting all data "from scratch" and plotting it directly onto a single map projection, pixel by pixel. In practice this is manifestly impossible, because data are going to be derived from multiple sources, and a malevolent deity will ensure that each source is at a different scale and compiled on maps using different projections. At one point, we wrote a series of computer programs that converted maps, pixel by pixel, from any widely-used map projection and scale to any other one **(Fig. 13)**. Eventually we had to write a program that would stretch any arbitrary shape into any other similarly arbitrary shape, because some of our best data sources turned out to be sketch maps drawn without rigorous geodetic control. Also remote sensing images have neither common scales nor projections as each is unique, and bringing a stack of them into common registry is no small feat.

I should not leave this subject without at least a word about the infamous "pseudo-patch" effect. **(Fig. 14)** In the best of all worlds, one would be able to go out into the world, identify each pixel on the ground, and measure each desired factor "on site." The data set thus obtained would be attached to that pixel, and that pixel alone. Such a procedure is somewhat less than practical. The more common reality is that each factor is mapped independently. Let us assume an ideal seldom realized. All the independently-produced factor maps are compiled originally on copies of the same base map, such that there are no scale or projection mis-matches. One of the data collectors is a soil scientist who maps the percentage of clay in the top 25 cm of the soil, and another is a botanist who maps the percentage of ground covered by grasses. When the two maps are placed in registry, it is noted that many of the boundaries are quite different, but that some of them are close together although not identical. The question immediately arises as to whether the near-common reaches of boundary

represent a naturalistic break such that both the soil and vegetation data are responding to a common condition, and therefore the boundaries should be identical, <u>or</u> whether the slight divergences are real, and the near-accordances only coincidence. It makes a difference, because, if they are real, a number of new terrain types have been created, and that adds to computational complexity. Furthermore, if the boundary should be common, then the "new" terrain types are actually "pseudo-patches" representing terrain types which do not exist.

Obviously careless data acquisition, or simple lack of detailed knowledge, can enormously amplify the number of pseudo-patches, thus introducing a whole host of "ghost" terrain types. In many instances, it is a problem that cannot be resolved, but equally often a bit of detective work will make it possible to arrive at a reasoned decision as to which option to accept. It should also be noted that simple errors in the registry of two or more maps can create the same effect, which is a compelling argument for taking care with registry.

Throughout all of this concept development, we were bedeviled by terminological confusion. For example, a term like <u>terrain type</u> meant quite different things to different people, and indeed we discovered that it could be used in two quite different senses by the same person, given different contexts. After we nearly came to blows a couple of times, we finally decided to agree on a restrictive and objective set of definitions. We soon arrived at this: A <u>terrain type</u> is a region throughout which the entire array of <u>factor values</u>, or <u>factor value classes</u>, is identical. A <u>landform</u> is a topographic feature of unique origin. A <u>landscape</u> is an aggregation of landforms <u>or</u> terrain types, so composed that the landforms or terrain types tend to repeat in an ordered mosaic over a region.

Obviously in any given geographic region, the number of terrain types is a function of the number of factors included in the set, and the number of factor value classes in each factor map. For example, if there are only two factors in the set, and only two factor value classes for each factor, the total number of possible terrain types is four. However, if three factors are mapped, and there are three factor value classes in each, then the total number of possible terrain types is 27. The numbers expand with appalling speed. A factor map set including 20 maps, each displaying 8 or 10 factor value classes, has an astronomical number of possibilities. Fortunately, nature is so ordered that not

all theoretical combinations actually occur, but, even so, the numbers of terrain types can be very large. When we first realized this, we assumed with the sublime faith of innocence that advances in computer technology would soon make it possible to manipulate the implied numbers. In the meantime, we compiled factor maps and terrain type map sets by hand!

It was easy to see that if the data storage problems could be solved, we had an environmental data information scheme of extraordinary power and flexibility. Sure enough, along toward the end of the development period NASA launched the LANDSAT, and a nice neat method of storing environmental factor data became commonplace. As most of you know, LANDSAT acquires images of the ground in four wavelength bands, and stores those numbers representing the radiance values pixel-by-pixel. The data stream is multiplexed and very compact. **(Fig. 15)** Our little group at WES was one of the very first agencies to use reels of raw LANDSAT data and convert it into imagery. It took us about 10 minutes to realize that a LANDSAT image was a precise analog of a terrain factor map set, because the four LANDSAT radiance bands are in effect separate `factor maps.' Thus, exactly the same procedure could be used to store and retrieve environmental data. The basic technique for manipulating the data was available, and would improve rapidly as computers increased in processing speed. The moral of this tale is that sometimes faith pays off! The proof of the thesis is that highly efficient GIS systems are currently operating on computer systems in many places, including here at WES.

Time constraints have prevented my telling the full story of the development of the terrain analysis concept for mobility purposes, and of the GIS concept in general. Even so, this account would not be complete without an acknowledgment that concepts were challenged and polished as a result of numerous interactions with scientists from Europe and elsewhere. Personnel from several of the Corps of Engineer laboratories, including WES, ETL (TEC), and CRREL, as well as from such Department of the Army labs as Aberdeen Proving Ground, participated in many joint enterprises with European scientists through various NATO research study groups, and with British, Canadian, and Australian scientists and engineers under the umbrella of the ABCA

organization. It is very nice to learn that such cooperation and interaction is still proceeding.

It would also be a very serious sin if I did not mention the support we received all along the line from our program managers in Washington. At the beginning it was a triumvirate consisting of Robert Phillipe, Robert F. Jackson, and Merrill V. Kreipke. Bob Phillipe died well before the first mobility model was up and running. He never saw the fruition of the effort, but Bob Jackson and Merrill Kreipke continued to support us every step of the way. In retrospect, it seems a remarkable act of faith. I can remember being asked to justify more than one wild-eyed plan, and at the time I viewed those sessions with fear and trembling. In retrospect, I can understand that they had two motivations. First, they were trying to make sure that we had thought the problem through, and second, they were acquiring ammunition to defend the programs in the inevitable budget scrambles. They served us, and their country, well, and deserve our unending gratitude.

Finally, I fear that, despite precautions, you will have somehow gotten the impression that there was a nice, smooth chain of concept development running through the entire period of 30 years or so. Nothing could be farther from the truth. It is easy to see the growth of the central ideas in retrospect, but at the time we were more often than not lost in a fog of confusion, facing problems for which there seemed no realistic solution. It has been said that new knowledge is only achieved by the sequential shattering of old paradigms, and I think there are few clearer examples of the truth of the adage than the history of quantitative terrain evaluation. Certainly a lot of our time was spent in unlearning much of what we absolutely knew to be true!

It is hard to climb out of old ruts!

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Figures for "The Origins and Development of Quantitative Terrain Evaluation"

Fig. 1: "Extreme Environments" Test Stations

Arctic: Ft.Wainwright, AL

Desert: Yuma Test Station, AZ

Tropic: Ft. Sherman, Panama Canal Zone

"Normal Environments" Test Facilities

Aberdeen Proving Ground, MD

Fort Knox, KY

Fort Belvoir, VA

(and other locations as needed)

Fig 2: Terrain Descriptors Used in Desert Terrain Analog Study

Factor	No. of classes
Characteristic Plan (defines characteristic plan shape of landforms)	4
Characteristic Occupance of Highlands (defines proportion of uplands and lowlands)	4
Characteristic Profile (defines characteristic cross-sectional shape of landforms)	3
Occurrence of slopes >50% (frequency of occurrence of steep slopes)	6
Characteristic slope (most frequent topographic slope)	7
Characteristic local relief (difference in elevation between ridge tops and adjacent drainage channel)	7
Soil Type (based on Unified Soil Classification System)	10
Soil Consistency (degree of cohesion)	11
Surface Rock (Type of exposed surface rock)	10

Vegetation physiognomy	12
(defined in terms of categories of:	
Ground cover (proportion of ground covered by all plants)	
Canopy Cover (proportion of ground covered by trees and scrub)	
Stem spacing (of trees and scrub)	
Stem diameter (of trees and scrub)	
Height (of trees and scrub)	
Crown diameter (of trees and scrub)	

Fig. 3: Range of Values Displayed by Alluvial Aprons

Characteristic Plan	2 of 4 categories
Characteristic Occupance of Highlands	4 of 4 categories
Characteristic Profile	2 of 2 categories
Occurrence of slopes >50%	4 of 6 categories
Characteristic slope	4 of 7 categories
Characteristic relief	4 of 7 categories
Soil types	7 of 10 categories
Soil consistency	8 of 11 categories
Surface rock	3 of 10 categories
Vegetation physiognomy	8 of 12 categories

Fig. 4: Types of models possible for Predicting Performance

1. Empirical models
2. Analytical models
3. Hybrid systems (combinations of empirical and analytical)

Fig. 5: Surface geometry obstacles to vehicle movement.

Fig. 6: Tree-stem distribution.

Fig. 7: Concept for analytical model of vehicle suspension system.

Fig. 8: Rice-fields dikes in Thailand (photographs).

Fig. 9: Competing Uses for a Vehicle Performance Prediction Model

1. Evaluate performance standards
2. Test and Evaluation (selection among competing vehciles)
3. Design (evaluation of drawing-board vehicles)
4. Tactical (performance prediction over large areas)

Fig. 10: Mapping concept for tactical uses of a mobility model.

Fig. 11: Map Patches and Pixel Aggregations

Fig. 12: Absolute Values and Classes (or categories)

Fig. 13: Map Registration

Fig. 14: The Pseudo-Patch Effect

Fig. 15: LANDSAT Data Stream = Factor Value Set

An Overview of WES Ground Mobility Research

A. A. Rula
WES Retired

1.0 Introduction

The purpose of my presentation is to present an overview of WES ground mobility research. Since WES activities in ground mobility research span a period of 50 years, time will only permit a general scope of activities and highlights of accomplishments. Perhaps details can be covered in appropriate work sessions. Please hold your questions until I have completed my presentation.

2.0 Background

The problems encountered during WW II with military vehicles attempting to negotiate off-road conditions signaled a need to develop relationships between trafficability of soils and the mobility of military vehicles. Early studies were assigned to the Corps of Engineers by R&D Division, War Department General Staff. In turn, Engineer Research Development Laboratory was assigned the development agency which was later transferred to WES.

3.0 Concepts

It was rather obvious that conceptually the capacity of a soil to withstand traffic of military vehicles is dependent upon the soil having sufficient bearing capacity to support the vehicle and having sufficient traction capacity to develop the resistance between the soil and traction elements to overcome the motion resistance.

Both bearing and traction capabilities are functions of the shearing resistance of the soil. In addition to the mass soil problem, strong plastic soils with a weak surface layer that create surface slipperiness was included along with soil adhesion to the running gear. Both latter considerations can cause inmobilizations.

4.0 Approach

The approach to each of the problem areas consisted of a rational method for measuring the soil strength by a shear test but the application of such results required a knowledge of the stresses in the soil mass under the load. Accurate information of the stresses was nonexistent and the time to develop such knowledge was not available nor was equipment available to measure the conventional soil parameters © and ø in wet surface soils. To my knowledge, we still cannot accurately predict stresses under a moving vehicle. Thus an empirical approach to the problem was adopted.

5.0 Equipment

Following an extensive laboratory study to evaluate soil strength measuring devices (cones, vanes, plates, etc.), sizes, shapes of soil penetration and shear devices, the cone penetrometer and a piston type density sampler were selected for further study. Following vehicle tests in natural soils, a soil remolding set of equipment was added to provide a measure of the anticipated amount of soil remolding.

The criteria for selecting equipment was dependent upon weight, component parts, ease of calibration, durability, capability of measuring a soil strength profile rapidly, and the potential for use by a soldier in the field.

The extended laboratory studies developed cone index, density-moisture content relations for a variety of soil types.

6.0 Pilot Self-Propelled Vehicle Tests

The next phase of the soil-vehicle programs included a local pilot program to conduct self-propelled and towed wheeled and tracked vehicles in large test lanes prepared in the natural environments. The soil in the test lanes was excavated, dried, pulverized, and mixed. The pits were lined with impervious material. The soil was placed dry and compacted in several lifts, and wetted to a moisture content which would yield the desired cone index. Tests were run at several geographical areas to obtain a range of plastic and nonelastic soils.

GO, NOGO, drawbar pull, motion resistance, and slope tests were conducted. The performance criterion designated by the military was 50-passes. This volume of traffic represented the number of vehicles that would be required to travel in trace when Division traffic had to be channelized.

These tests produced data that lead to the assignment of the critical layer and cone index for different weight classes of wheeled and tracked self-propelled and towed vehicles to meet the performance requirements. Although the cone index unit is in psi, it is considered a dimensionless number because a cone index of 10 in the critical layer does not mean that a vehicle with a 10 psi ground pressure can negotiate the area. The number assigned as GO for a prescribed number of

passes is termed the vehicle cone index. The vehicle cone index numbers have been limited to 1 and 50 pass capabilities.

In addition, the data base was used to develop the mobility index equations which can be used to compute the minimum soil strength requirement for untested vehicles.

7.0 Self-Propelled Vehicles Tests in Natural Soils

The vehicle test program was next expanded to verify the results of the prepared soil tests to natural soil conditions. A range by weight and type of wheeled and tracked vehicles were used in the program. Tests were run locally and in other areas in a range of fine-grained soils. The results indicated that a higher cone index strength was required in natural soil than in prepared soils to achieve the same level of performance. This phenomenon was identified as soil remolding for the designated critical layer. Soil remolding by vehicle traffic is the result of the redistribution of the soil water with some soil densification causing pore water pressure and soil/water mixing resulting in a reduction in soil strength.

The product of the cone index and remolding index for the same soil layer was termed rating cone index.

8.0 Soil Classification

The vehicle test soil data and special studies conducted in different geographic areas during the wet season produced a data base from which soils could be classified during the wet season on the basis of their remolding indices and cone index values. It was determined that the Unified Soil Classification

System was satisfactory for soil trafficability purposes. Basically, highly plastic soils usually retain 85 to 95 percent of their cone index value after remolding. Silty clay and silty soils retain about 30 to 50 percent and silty sand about 5 to 15 percent if a vehicle produces load liquification on the first pass. This is common when the water table is within the surface 2 feet. Desert sand with some silt present becomes somewhat brittle at low moisture content (0.5 to 1.0%). After traffic the sand becomes loose and sugary with a cone index about 25% of the original strength.

9.0 Clean Sand Self-Propelled-Vehicle Tests

In the early 1959's at the request of the Navy the vehicle test program was expand to include clean sands.

Tests were conducted on moist and wet beach sands and dry, western dune sands. During the initial test program, a variety of shear plate, vane devices and penetrometers were used. At the end of an equipment evaluation period the cone penetrometer was selected as the soil strength measuring device of choice and a device was designed for measuring the density of loose sand. Soil type, profile strength, density and moisture content data were collected.

Most sand conditions tested were trafficable to tracked vehicles and wheeled vehicles unless the wheeled vehicles operated at high tire pressure. The first pass was the most critical and the surface 6-in. layer was identified as the critical layer. An empirical mobility index equation which completed the minimum cone index for vehicle GO conditions was developed for wheeled vehicles. The equation accounts for tire deflection and other tire characteristics.

A companion laboratory test program was also conducted on clean sands and a heavy clay soil at several strength/density combinations. Tires of different sizes, deflections, and wheel loads were tested. Limited tests were conducted with a track device in prepared heavy soil. The data base was used to develop numerics that related soil and test device characteristics to performance in terms of drawbar pull, sinkage, motion resistance, torque, etc. This work will be covered in detail later in the program.

10. Soil Moisture - Strength Relations

Once methods and techniques were developed to measure and predict soil-vehicle performance, the scope of soil trafficability investigations were extended to include an understanding of the time-spatial relations of soil strength variations. Since it was established that soil type, moisture content, climate, topography and landuse impacted on surface soil strength, a program was established to develop soil moisture-strength relations for 0- to 6-in. And 6- to 12-in critical soil layer for the parameters that influence soil moisture on a daily and/or seasonal basis. The Forest Service assisted in these studies.

The approach used in the soil moisture prediction study considered pertinent site and soil factors and daily rainfall amount. The method was essentially a book keeping method which increased the soil moisture on days of rain in the 0- to 6-in. and 6- to 12-in. layers as a function of the available soil storage and the amount of rainfall as storm size. If the rainfall amount was less than the available storage in the 0- to 12- in. layer it was identified as a Class I storm and Class II storm if the rainfall was equal to or greater than available storage in the 0-12 in. layer. Site accretion relations were used to wet the soil on the days it

rained, and decreased daily by depletion curves developed from field data for the four seasons.

Studies were conducted in several climate zones and site factors. The data collected were also used to develop soil moisture-rating cone index relations for each site and critical layers. Special equipment was used in measuring soil moisture on a daily basis. The moisture sensors were placed at 3 in. vertical increments and they were calibrated using bulk soil samples taken from the site.

11. Vehicle Dynamics

As the scope of the soil trafficability studies were expanded, it became apparent that the military was also concerned with the speed that vehicles could travel over a variety of negotiable terrains. Time to complete a mission became an important performance parameter. It was obvious that terrain roughness and discrete obstacles produced adverse vehicle motions that limit vehicle speed because of driver, cargo, or vehicle component tolerances.

Vehicle dynamics research was initiated at WES in the later 1960's. The approach modeled mathematically the interaction among terrain, ground-crawling vehicle parameters and driver response to continuous vibration and shock levels for basic suspension types. The structure of the model is composed of an assemblage of lumped masses, beams, springs and damper elements arranged to represent a specific vehicle. Differential equations describe the motions of the masses analyzed as time histories.

The terrain is considered as an unyielding surface without allowance for modification by vehicle traffic. The terrain is represented by a series of x-y data points connected together by straight line segments. The profile data are

processed using filtering and statistical techniques to obtain a terrain description in terms of root mean square elevation that is a measure of surface roughness. Discrete obstacles are described as geometric cross sections. Model outputs are usually expressed in terms of relations between speed-ride quality and shock referenced to established driver location and vertical acceleration tolerance limits.

Laboratory and field tests have demonstrated that vertical acceleration in terms of absorbed power can be correlated with operator ride quality. A 6-watt absorbed power level was adopted as the comfort level that the vehicle driver could perform satisfactory. Absorbed power is a measure of the level of vibration intensity that the operator in experiencing. A ride meter was developed to measure absorbed power. Companion electronic equipment was designed to get a real time measure of absorbed power. Shock is described as a single vertical acceleration event, and 2.5g has been established as the driver limit.

The VEHDYN model and associated programs have contributed to a variety of applications involving terrain, vehicle motion and driver response interactions that are measurable and testable.

12. Other Terrain - Vehicle Relations

In the early 1960's the Army became more interested in mobility environmental research. The Army's interest was expanded into a long range research program to develop and apply new and existing methods for measuring and predicting in quantitative terms the effects of environmental factors on ground vehicles operating in a variety of environments.

With such an extended scope, WES examined its research program to determine what terrain factors that affected ground mobility that were not accounted for. A list of environmental factors in terms of type and degree of affect on ground mobility was prepared. The inventory identified the following list of environmental factor - vehicle relations that requires research and development.

- On-road mobility
- Vegetation override
- Stream crossing
- Visibility
- Maneuvering through an obstacle field
- Maneuvering and override optimization

Research programs were established to develop the necessary environmental factor - vehicle performance models to quantify the affects on vehicle speed performance. In most of the model developments many terrain attributes had to be considered. For example the on-road model requires a consideration of the affects of visibility, surface roughness, grade, and curvature. Stream crossing required the consideration of the affects of stream geometry, soil strength, water depth, stream velocity, and so on. Suitable models were developed for predicting the affects of these factors on vehicle speed.

13. Ground Mobility Model

In the early 1970's the Army was concerned with the variety of so called mobility models that were available in the literature. In order to evaluate which models were available the Army funded a study to identify, describe, and

evaluate existing ground mobility models, and recommend an overall ground mobility model for the Army's use. WES drew the assignment.

The report proposed an overall ground mobility model along with its advantages, disadvantages, and research needed to computerize all the so-called submodels into an overall model. The overall mobility model was developed by WES and TACOM. The overall model was divided into three parts. One model addressed the areal terrain - vehicle speed predictions. Another handled the time to cross linear terrain features such as streams and ditches, and a third model predicted road speeds.

In 1972 the ground mobility model was assigned the title of Army Mobility. At a later date it was accepted by NATO and the model identifier became NATO Reference Mobility Model (NRMM). The model has been updated periodically to extend its use. NRMM can produce a variety of outputs useful to vehicle designers, developers, and users of military equipment in a variety of military operations. The model has been used to provide answers to many mobility related problems.

14. <u>Terrain Mapping</u>

Of importance to the military is a map that identifies the different terrain conditions that impact on operation performances. In the early years, maps portrayed only GO and NOGO conditions during the wet and dry seasons for a tank and wheeled vehicles. The advent of the quantification of terrain and the Army Mobility model paved the way to conduct more sophisticated studies portraying terrain unit speeds, and a variety of graphics, statistics, optimum routes, terrain factors limiting speed and so on.

Appendix C
Workshop Papers

RECENT ADVANCES AND OPEN PROBLEMS IN THE STATISTICAL MODELLING OF TOPOGRAPHY AND RAINFALL

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INTRODUCTION

Among the variables that are most critical to mobility are topography and precipitation. Either directly or indirectly (e.g. through channel flow and soil moisture) these variables enter prominently in algorithms that evaluate vehicle performance and assess alternate routes. Ideally, topography can be measured at the required level of detail and past rainfall or current soil moisture can be inferred from remote sensing. However, in combat situations, the resolution and accuracy that can be attained are typically poor and the information available must be complemented by simulation to produce scenarios that are both realistic and detailed. In the case of rainfall, future events cannot obviously be measured, so that simulation plays an even greater role in anticipating terrain conditions. Simulation of both topography and rainfall is also important to generate "what if" scenarios, for example for use in training exercises. In what follows, we briefly review recent developments in the statistical modelling and simulation of topography and rainfall and describe ongoing work of our group at MIT.

TOPOGRAPHY

Some of the most spectacular computer simulations of the earth topography are the images produced as realizations of so-called fractional Brownian motion or fBm (e.g. Voss, 1985). fBm is a random process model that exploits a property called self-similarity. According to this property, if a portion of the earth surface is stretched in both horizontal directions by a given factor while the elevation is simultaneously stretched by a different factor, then the resulting scaled topography is statistically identical to the original one. This principle (with some important variants) has been at the core of much recent research in statistical geomorphology and hydrology. The reasons for interest in self-similarity are many and range from understanding the fundamental genetic processes and principles that shape our seemingly very complex environment to simplifying statistical models, expediting simulation, and efficiently assimilating data at different scales. These same features make self-similarity attractive for mobility applications.

fBm realizations may be visually pleasing, but before the fBm model can be used for more serious purposes, several questions need to be answered: does real topography display self-similarity and, if it does, is fBm the appropriate model to use or are there better alternatives? Does fBm or any other self-similar model satisfy known properties

of topography at the river basin scale, such as draining, channel network connectivity and other Hortonian invariants, and the "Area-Slope" relation? If not, how can one modify the models so that they do have these properties?

At the present time we can answer only some of these questions. One thing we know is that fBm is not a good model of topograhy. This is because: 1. fBm is nonstationary, meaning that it produces surfaces with different statistical characteristics at different locations. 2. fBm is a zero-mean process with marginal normal distributions, with the implication that fBm and -fBm are statistically identical. However, valleys do not look like upside-down ridges and, in many cases, topography is a positive and hence non-normal anomaly above sea level or an alluvial plain. 3. fBm fails to reproduce many of the characteristics of river basins mentioned above and has poor drainage properties, resulting in landscapes with an excessive number of "pits" and "lakes".

Improvements over fBm, especially relative to Issues 1 and 2, are obtained by considering self-similar pulse-based models. There are two main classes of such models: Fractional Sums of Pulses (FSP) models and Iterated Random Pulse (IRP) models. The former view topography as the sum of pulses of different sizes, whereas the latter represent topography as the sum of pulses of the same size, but distributed spatially so that they produce fluctuations at all scales. FSP models were developed in the 1960's in the area of communication. They have been applied to topography by Bell (1975) and rediscovered for application to rainfall by Lovejoy and Mandelbrot (1985). By contrast, IRP models have been developed very recently by our group at MIT (Veneziano et al., 1995). The original application of IRP models has been to "width functions", which are important morphological characteristics of drainage basins, but these models also produce realistic topographic surfaces and space-time rainfall patterns. Examples of topographies simulated by an IRP model using different values of a roughness parameter γ are shown in Figure 1. As one can see, the functions are entirely positive and are clearly better draining than fBm surfaces. By controlling the spatial density of the pulses and possibly other parameters, one can model various other features of topography, such as localized mountains, ridges, etc. Both FSP and IRP models are self-similar over a finite range of scales, which can be controlled by the user.

Although they are superior to fBm, pulse-based models still do not satisfy various morphological laws at the basin and sub-basin levels. No statistical model we know of has this capability, although there are several physical models that produce realistic topographies at small scales. These are mainly models that simulate the evolution of topography by numerically representing fluvial erosion, avalanching and other transport phenomena in river channels and on the hillslopes. Our group has been very active in the development of such models (e.g. Willgoose et al., 1991; Moglen and Bras, 1994). An outstanding problem is how to merge the large scale representation and inference capabilities of the statistical models with the detailed landscape realism of the physical models. We are currently working on this problem, which we regard as critical to the development of topographic relief simulators for mobility applications.

Our approach is to first use a statistical model, e.g. of the FSP or IRP type, to generate a large-scale "statistical topography" and then use this statistical topography as input to simplified (for numerical efficiency) physical models to produce realistic details at the smaller scales.

RAINFALL

Rainfall is a complex phenomenon and is more difficult to represent statistically than topography, due to its larger dimensionality (at least 2 spatial dimensions plus time). Rainfall also displays a more complex type of self-similarity, called multifractality. Earlier precipitation models did not recognize multifractality and were based on the superposition of contributions from convective cells; see for example Waymire and Gupta (1981). The organization of rainfall at different scales is recognized in these models through the clustering of cells in space and time. A problem with cell-based models is that they contain a very large number of parameters, which are difficult to estimate. Another limitation is that they do not take advantage of self-similarity.

Emphasis on scale invariance has led since the mid 1980's to the formulation of so-called multifractal models, which display no preferential scale and explain rainfall through a multiplicative mechanism similar to the energy cascade in turbulence; see for example Schertzer and Lovejoy (1987) and Gupta and Waymire (1993). Multifractal processes are generally obtained as products of independent nonnegative random functions which are identical in distribution after their supports have been stretched or compressed by suitable factors. A characteristic of multifractal processes is that the power spectrum of the log process, when it exists, has an $|\underline{\omega}|^{-d}$ decay, where d is the space dimension (e.g. d = 1 for rainfall in time at a given location) and $|\underline{\omega}|$ is the frequency vector.

There is increasing empirical evidence that intense rainfall is indeed best represented by a multiplicative scheme, but that the spectrum of log rainfall does not behave like $|\underline{\omega}|^{-d}$, either in space or in time (Crane, 1990; Perica and Foufoula-Georgiou, 1995; Veneziano et al., 1996). Departure of the spectrum from this power form has also been justified on physical grounds; see Crane (1990).

From this physical and statistical evidence one must conclude that multiplicative self-similarity of a type different from multifractal scaling is involved in spatial and temporal rainfall. To identify a suitable model, we have defined a wide class of multiplicative models which includes multifractal processes as a special case and is rich enough to capture the essential features of space-time precipitation. The specific type of model and its parameters must be identified through data analysis. Thus far, we have completed the model identification/parameter estimation tasks only for rainfall in time. Using a set of high-resolution rainfall records from a single station, we have found that a lognormal process with log spectrum of the segmented power type (of the type $|\omega|^{-\beta}$, with β that varies in different frequency ranges) fits the data quite well.

Specifically, we have identified 4 different spectral regimes between scales from a few seconds to several hours and related them to specific dynamic processes at the mesoscale or microscale in a turbulent atmosphere. Compared to existing alternatives, the model is very easy to fit to data and to simulate. An example of registered and simulated rainfall, the latter using parameters extracted from the former, is shown in Figure 2.

The analysis and model illustrated above should be extended to space-time rainfall. It should be noted that the lognormal model is not the only one possible for rainfall. Alternatives include certain classes of pulse processes of the IRP type described earlier for topography. While we have not yet tried to formally identify and fit models of this type to rainfall, simulations using reasonable parameters produce very realistic-looking "rainfall" patterns. An example is shown in Figure 3. We plan to continue this line of work in the near future.

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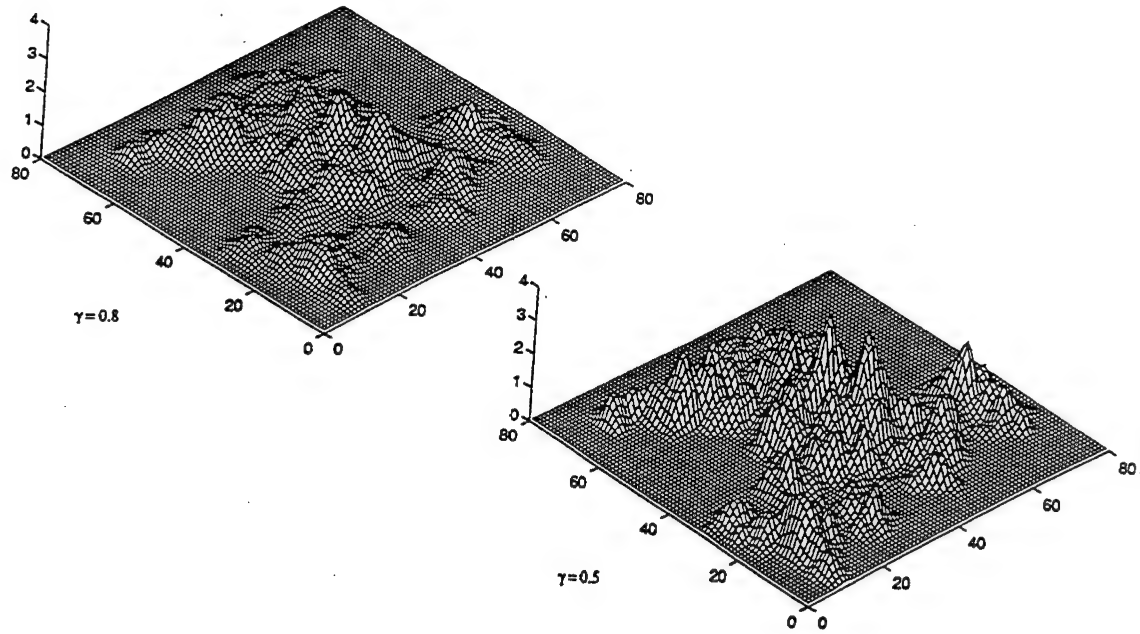

Figure 1 - Simulated "topographies" with different roughness γ, using an IRP model.

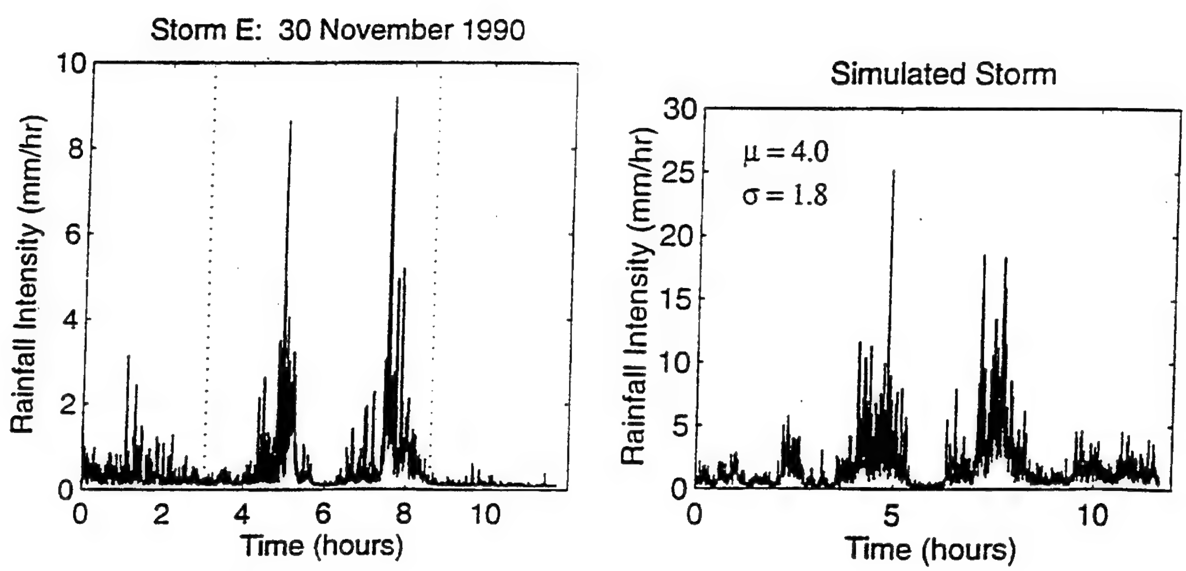

Figure 2 - Actual rainrate record (left) and simulation using the lognormal model (right).

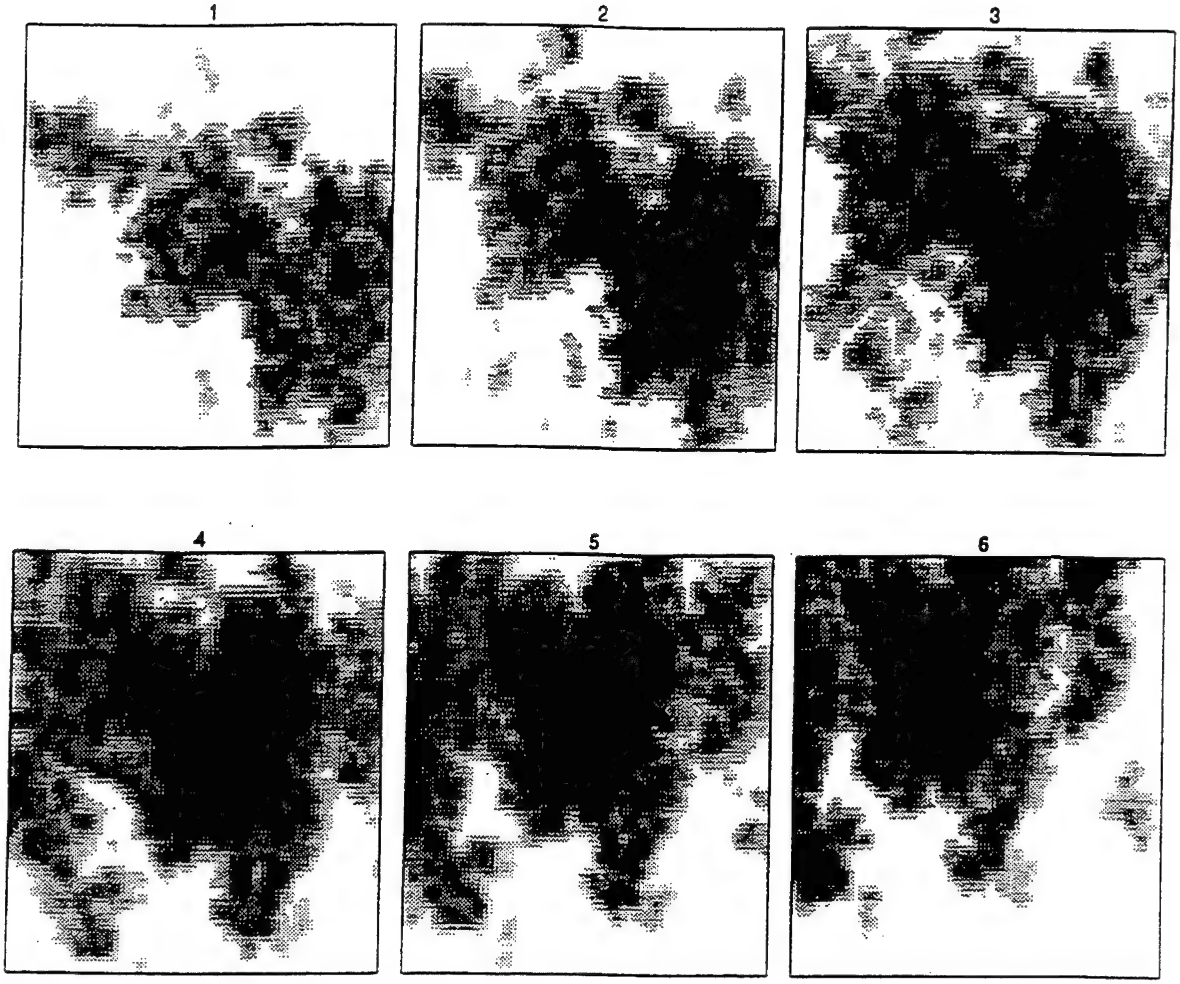

Figure 3 - Simulated "rainfall" map sequence using an Iterated Random Pulse model. The simulation includes a translation velocity towards Northwest.

SNOW PROPERTIES AND MEASUREMENT
For Use In Mobility Algorithms

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Introduction

Snow, like soil comes in many shapes, sizes and classifications, additionally its properties change easily with time. Snow can have almost no shear or initial compressive strength or at the other extreme, can be nearly as hard as ice. A temperature gradient in a snow pack will cause moisture vapor to move between particles, changing their size and shape as well as intergranular bond strength. Once snow is disturbed it is not possible to reconstitute it to its original properties. This makes laboratory testing difficult.

Winter mobility researchers at CRREL have developed terrain interaction algorithms from direct measurement of snow properties. Other research at CRREl is oriented towards developing algorithms and techniques to determine snow cover properties and how they change.

In this presentation, I will discuss snow properties, their measurement or estimation and their effects on mobility.

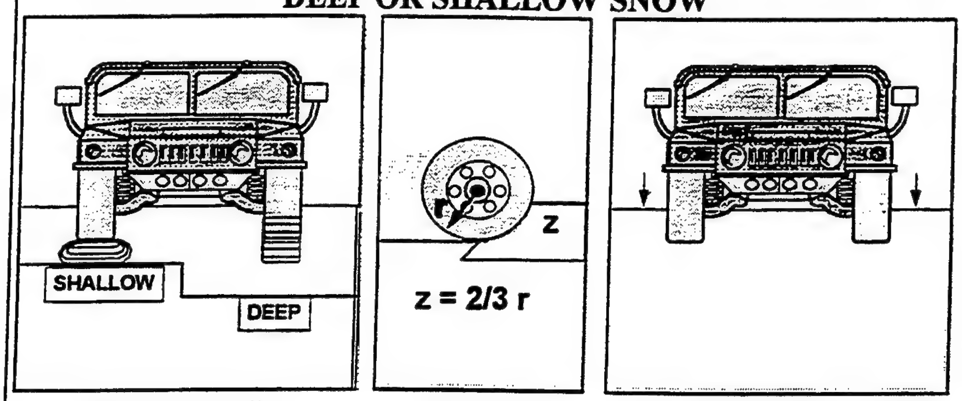
PRIMARY CHARACTERISTICS OF SNOW

Density	Depth
Strength	Hardness
Temperature	Grain size
Liquid water content	Grain shape
Stratigraphy	

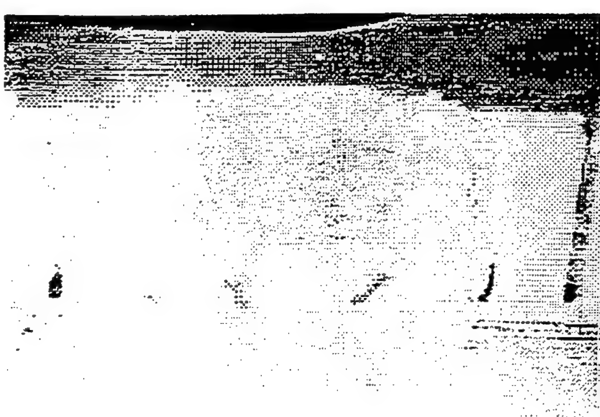
These are the primary characteristics of snow. Only depth and density are currently required for our mobility models. These are easily measured. Earlier U.S. models and some current Canadian models require extensive strength and hardness measurements.

Here the density of the pressure bulb is being measured, a small sampling device has been inserted into the compacted snow. A balance scale, combined with the known volume is used to determine the density of snow in g/cm^3.

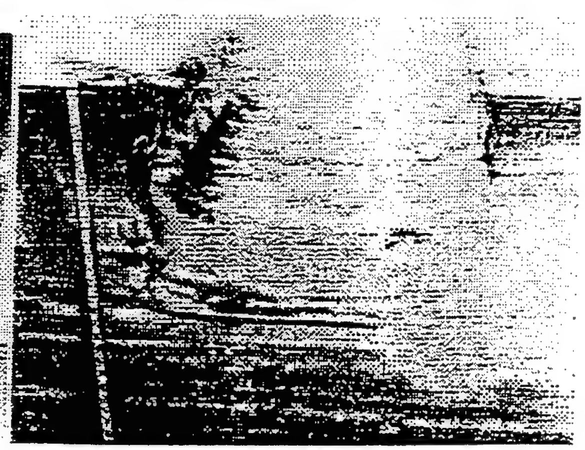
DEEP OR SHALLOW SNOW



Pressure Bulb Sinkage Undercarriage Clearance



Shallow snow



Deep Snow

Snow depth is very important in predicting vehicle mobility, deep snow will inhibit mobility on level terrain (to the point of no-go), while shallow snow, in general, causes no-go conditions only on slopes. Snow is considered to be deep if any of the three conditions shown in the figure are met. Traction is reduced on all snow surfaces. Variability on a test course must be measured manually, generally an average value is reported for specific tests. In NRMM, each terrain unit can have one value of depth and density or a scenario of one depth and density can be selected.

SNOW COVER SCENARIOS

	Density (g/cm^3)	Depth (cm)
Alaska		
Average	0.230	50
Worst case	0.425	125
Central Germany		
Average	0.275	25
Worst case	0.400	60
Korea		
Average	0.275	18
Worst case	0.400	38

Here are snow cover scenarios recently developed. In general, the density of undisturbed snow can be as low as 0.04 and as high as 0.5. Snow greater than 0.55 is considered "hard packed snow" and is obtained after repeated vehicle passes or intentional processing into a snow road.

SNOW STRENGTH AND HARDNESS

Canadian hardness gauge
Rammsonde/drop hammer penetrometers

Shear vane/pressure-sinkage (Bevameter)

Thin walled tube penetrometer
Direct shear methods (shear box)

Snow strength and hardness can be measured a number of ways. The first set of devices are hand held. The Canadian hardness gauge is used in shallow snow covers, and the penetrometers in deep snow. Deep snow is often fairly hard, often times hard enough to walk on. As snow becomes harder, it becomes easier to find correlations between penetrometer results and mobility parameters or standard measures of strength such as shear strength or CBR. Penetrometers have been used extensively in the Arctic, Antarctic and on the Greenland Ice cap.

The Bevameter was at one time used extensively in snow, and it still finds some use in snow (we used it for some of the wheels/tracks study and the Canadians still use it). This device is not currently "in favor" for a number reasons, we have not found algorithms that successfully use the data produced and its use requires significant resources.

These last two devices, the thim walled tube and shear box, are being examined to determine shear strengths without compressing the snow (which increases shear strength).

We think that the initial bond breakage between particles and then subsequent friction between particles and particle deformation is important, and must be understood before improved resistance algorithms can be developed. I anticipate that at least one more snow property or index will be required in future algorithms.

Temperature	Grain size
Liquid water content	Grain shape
Stratigraphy	

These remaining snow properties clearly affect the others and each other. Temperature is easily measured, but the snow cover is almost never isothermal, temperatures at the ground/snow interface are usually warmer then at the snow/air interface and it is this temperature difference that causes snow properties to change. A temperature history index may give us an indicator of strength. Grain size and shape require only a magnifying glass and a knowledge of snow shapes. Snow moisture can be measured with a moisture sensor (capacitance meter); rules of thumb can also provide information about water content. However, no snow mobility algorithm uses theses properties.

Stratigraphy or layering of snow is also an important property, denser snow is usually found at the base of a snow cover, current algorithms were developed using a weighted average density.

VARIATIONS IN SNOW COVER PROPERTIES

Global - 6 Classes of seasonal snow, can be identified by global climatology.

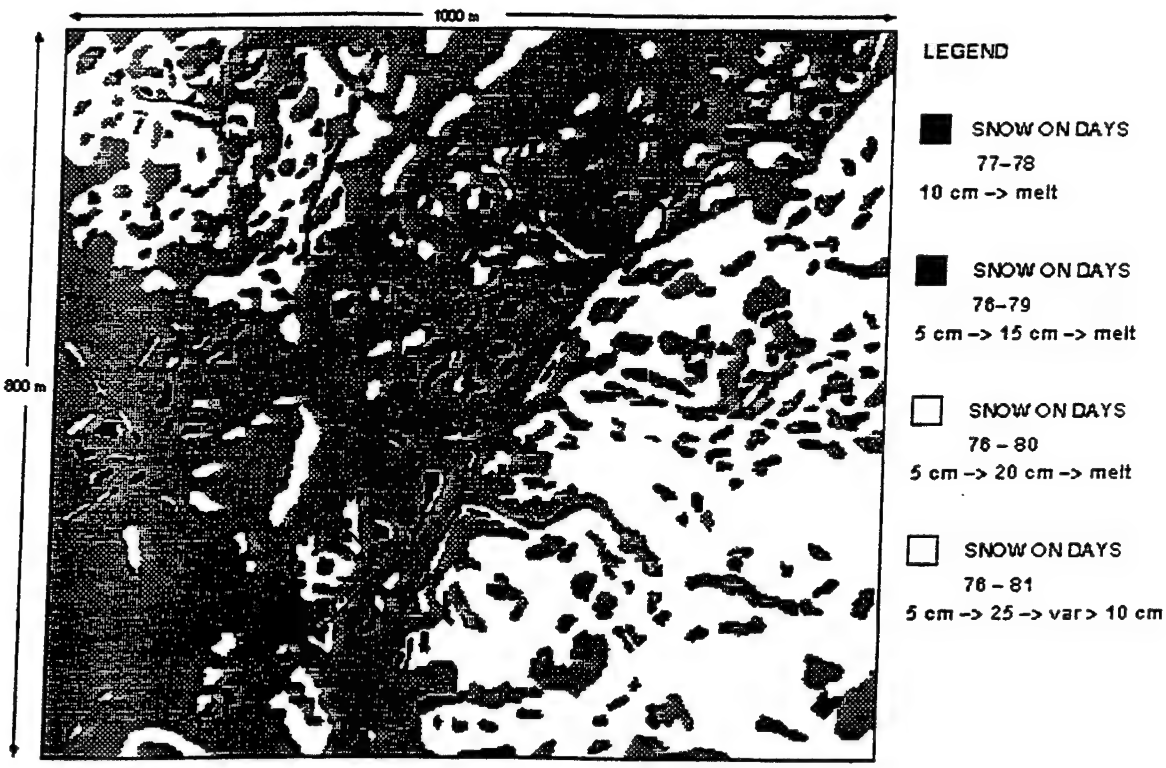
Tundra → Taiga →
Alpine → Maritime →
Ephemeral
Prairie

A new snow classification system for seasonal snow was recently developed, it consists of 6 classes with transitional characteristics between classes shown by the arrows. Once an area is classed, we can infer snow properties, including range of density and depth, expected stratigraphy, and grain characteristics. Current work is examining how bulk density changes with time within a class.

VARIATIONS IN SNOW COVER PROPERTIES (cont.)

Distributed snow process model

For variations of snow characteristics over small terrain segments, an image processing approach is beginning to yield results at one meter resolution. Beginning with maps of terrain, soil, vegetation and initial snow information, changes in the snow cover characteristics have been determined. The method uses a one dimensional heat and mass balance model with initial data and local meteorological data. Depth, density, grain radius, and temperature and are obtained at 1-meter resolution.



Variability of threshold snow depths over Camp Grayling test site 16-21 March 1994.
Validation – extensive at site E (diamond): depth accuracy > 75%; aerial accuracy > 90%; locational accuracy > 70%

This picture shows how snow cover was mapped over a period of 4 days, the legend indicates changes in snow depth with time. For example on days 77-78 the snow was initially at 10 cm or less and melted. The white indicates that the snow depth changed from 5 cm to greater than 25 then varied in depth, with 10 cm or more at the end of the period. Depth accuracy was greater than 75% in the validation region.

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STOCHASTIC MOBILITY MODELING: FORECASTING TEMPORAL CHANGES IN VEHICLE TRACTION

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ABSTRACT

A methodology is developed for off-road vehicle routing that accounts for significant uncertainties in time variations of soil strength and other input parameters. Core features of the methodology include abilities to forecast temporal changes in soil strength along with the effects of uncertainty in the selection of off-road routes for wheeled and tracked vehicles.

It is well known that soil strength is an important indicator of mobility because it affects the vehicle's traction and resistance to forward movement. Therefore soil strength is commonly used as a measure of the ability of a vehicle to traverse a specified segment of terrain. Previous work on predicting soil strength for purposes of terrain analysis has contributed to the creation of a model useful for mobility mission planning. This study seeks to enhance this model through an adaptation of the well-accepted Box-Jenkins technique to forecast changes in soil strength. The North American Treaty Organization (NATO) Reference Mobility Model will be used to monitor changes in vehicle mobility as a function of soil strength variations.

A case study is presented to demonstrate the use of the time series model to forecast soil strength (using cone index readings) over a two-year period. The implementation of the model for planning off-road routes is presented with explanations on the use of temporal variations in soil strength and traction. The selection of optimal routing for unit movement based on past seasonal changes in weather conditions is employed. A number of important conclusions drawn in this study are presented and discussed.

INTRODUCTION

Area of Concern. Modeling the off-road movement of ground vehicles has been conducted for many years within the U.S. These mobility models consider terrain, road, and tactical gap attributes along with vehicle geometries and human factors (Haley, 1979)(1). The fundamental output is a mobility forecast based on speed predictions keyed to specific areal units of terrain a specific road network. The mobility predictions are used to create mobility overlays which provide the user indications of where a particular vehicle can travel off-road. Figure 1 illustrates a mobility speed

overlay for a tracked vehicle operating in the Lauterbach Germany Quadrangle. The map depicts a wet condition or average soil strengths during the wettest 30 day period of the year.

Mobility models have been successfully used as procurement tools for the selection of the best qualified (from a mobility standpoint) wheeled and tracked vehicles to operate in various regional areas. As computers were reduced in size and increased in speed, these models were gradually used in field exercises, allowing the troops to plan movements, define counter-mobility measures, and identify lines of communications. This new operational environment brought forth concerns of the integrity of the terrain data, the exactness of the internal curve fits, and the reliability of the mobility speed predictions in light of these uncertainties. These input uncertainties include temporal, spatial, and random variations. This study seeks to address an approach for dealing with temporal precision with a mobility factor, specifically soil strength.

Scope of Work. Soil strength variation is a time dependent factor based on climatic conditions and terrain considerations. Giving a soil strength forecast as a function of cyclic patterns provides a prediction interval or reliability estimate of future changes in mobility. A time series model was developed in this study to give forecasts of changes in ground mobility with time. This forecasting of temporal changes in mobility not only provides a model that predicts a nominal soil strength for a given time period but also a maximum and minimum soil strength that can be used to define levels of risk for vehicle movement and windows of opportunity.

From a mobility standpoint, the minimum forecasted soil strength will define the possibility of vehicle immobilization. Moisture content and soil strength for geotechnical material are highly correlated. Therefore, a successful temporal model is needed where seasonal rainfall changes are significant. This study seeks to extend temporal analysis of soil strength to develop a forecasting tool.

Past Studies. Time series modeling of terrain parameters has been conducted by many researchers, such as Bilonick (1984)(2). Bilonick modeled the acid rain fluctuations in the northeastern United States with time using a Box-Jenkins model. The sparse network of weather stations provided enough information to allow the state and Federal agencies with data to forecast the nominal, maximum, and minimum acid concentrations in rainfall for various regions based on historic data.

Extensions of Box-Jenkins models have been used by Caron et al. (1992)(3) to predict soil stability for agricultural purposes, when given soil moisture content. Caron's study was directed at prediction of soil moisture content over time to support decisions on irrigation for crops. Rada et al. (1989)(4) uses the Sellers et al. (1986)(5) method to extend the research of temporal changes in soil stability a step further. Rada models relationships between soil moisture and soil strength in terms of the California Bearing Ratio for various soil types and uses this relationship to define degradation of roads due to seasonal weaknesses in the subgrade when excessive moisture is retained. These studies provided a basis for using a Box Jenkins approach for soil strength forecasts relative to mobility.

DISCUSSION

Time Series Modeling of Seasonal Data. Time dependent relationships are defined by a series of observations made sequentially over time. If a successful time series model is created, it is because cyclic patterns in the data are clear; that is, strong correlations lead the observer to expect similar events to occur in the future. If these cyclic trends in the data occur at even intervals and are independent, a time series model can be used to define correlations between the events, such as the Box-Jenkins Autoregressive Integrated Moving Average model. Recent investigations with neural networks to forecast trends in time series data have met with success. For the development of a Box-Jenkins model, stationary time sequences are required to determine the correlation between these events. A non-stationary time series is a sequence of events that has some well-defined trend (such as seasonal increases of soil strength with time). Where non-stationary data exist, an additional step is necessary to define the trend. The trend must then be added back when forecast procedure is made.

Climatic Considerations for Soil Strength Modeling. Soil strength modeling relies on a) prior knowledge of the soil type, b) drainage of the terrain, and c) past, present, and future climatic conditions. The model is defined by historic soil strength data based on the soil type, precipitation, and drainage of the area of interest. For this study, the Soil Moisture Soil Prediction model is used to generate historic soil strength readings in terms of cone index for this study. The Box-Jenkins model is data driven. The model requires less direct knowledge of the terrain, such that inferences on satellite imagery, that may be conducted in future studies, can be used to generate the historic soil strength data.

The Role of Soil Strength/Soil Moisture in Vehicle Mobility Modeling. Vehicle performance off-road is defined in terms of a vehicles available tractive effort and respective speed. Tractive effort is the sum of the vehicles drawbar pull and ability to overcome resistance of the soil. The tests used to measure the tractive performance of a vehicle consists of attaching a load measuring device between the test vehicle and a load vehicle. The test vehicle accelerates to maximum speed with the load vehicle following behind and then the load vehicle gradually applies brakes slowing the test vehicle down. A load cell attached between the two vehicles measures the "drawbar pull" while strain gages attached to the drive train of the vehicle measure the torque. The difference between these two outputs is the motion resistance acting against the forward movement of the vehicle. Surface slippery conditions on off-road areas reduce the available traction of the vehicle by reducing the drawbar pull of the vehicle. As the vehicle encounters soft soil conditions the available tractive effort is reduced due to the motion resistance acting against the vehicle as a result of sinkage and the vehicle inability to maintain adequate traction. Vehicle immobilization in an off-road environment occurs in soft soils when the vehicle is unable to maintain an adequate tractive effort.

Two predominate surface conditions occur on off-road material that affect vehicle mobility the first is a wet slippery condition the second is more a function of sinkage simply referred to as a wet condition. Rainfall of .25 inches or more on fine grain materials will result in a wet slippery

condition for several hours until the excess moisture has evaporated or been absorbed by the soil. The evaporation rate of the area and the canopy cover will determine the length of time this condition will exist. The moisture content of the surface during wet slippery conditions range between 32 to 29 percent of the weight of the materiel on the surface and the moisture content reduces rapidly to 15 to 19 percent from 2 to 6 inches (Moore 93). The soil strength typically ranges from 130 psi to 180 psi for the top 1 inch and 300 psi or more for 2 inches and deeper. Vehicle drawbar pull will be reduced during wet slippery conditions by as much as 20 percent of the vehicle weight. Prediction of a wet slippery condition requires short term modeling of rainfall, this study attempts to focus on long term changes in soil strength as indicated by the wet condition.

Wet soils are depicted by soils whose strength and moisture content does not change rapidly from the surface down to 36 inches. Reduction in the traction is caused by excessive motion resistance caused by sinkage (insufficient bearing capacity of the soil to support the vehicle) and shearing of the soil. The shear capacity and bearing capacity of a soil are related to the soil type, moisture content, overburden pressure (contact pressure of the vehicle), and any prior consolidation of the soil. Traction of the vehicle is provided by soil at depths of 0 to 36 inches. After about 36 inches, the weight of the vehicle has dissipated, and the shearing action and sinkage of the tire is insignificant. Figure 1 illustrates the relationship between drawbar pull and the strength of the soil in terms of excess remold cone index. The excess remold cone index is the cone index above the VCI_1. The WES cone penetrometer is used to determine the strength of the soil with depth. The minimum remold cone index for the vehicle to complete one pass is defined as the vehicle cone index (VCI_1). The VCI_1 of several wheeled and tracked vehicles are shown in Figure 2. Figure 2 indicates that the average minimum soil strength requirement for wheeled vehicles is, on the average, higher than that for tracked vehicles. The low contact pressures of tracked vehicles account for this difference. Figure 2 also indicates that soil strengths below a 35 remold cone index are of concern to most wheeled and tracked vehicles. Figure 1 illustrates that most vehicles have no traction problems 50 points above their vehicle cone index, therefore, for mapping purposes, only areas of soil strengths less than an 85 remold cone index will be mapped in this study. The relationship between soil strength in terms of the remold cone index and soil moisture content is shown in Figure 3 for sites in Louisiana, Montana, and data collected out of some studies identified simply as old data which was collected in Costa Rica and Asia. The plot indicates that moisture contents below 10% for CH clays map to the soil strengths that affect off road traction. The prediction of soil moisture content is accounted for from many researchers. Sellers and Mintz (1985)(4) have developed models for determining moisture content for a given soil type and soil depth over time for each of three layers. Equation 1 gives the relationship between soil strength and moisture content where the empirical constants are summarized by:

Layer 1 (Surface)

$$\frac{\delta W_1}{\delta t}=\frac{1}{\theta_s * D_1}[P-Q_{1,2}-\frac{1}{\rho_w}(E_1)]$$

Layer 2

$$\frac{\delta W_2}{\delta t}=\frac{1}{\theta_s D_2}[Q_{1,2}-Q_{2,3}-\frac{1}{\rho_w}(E_2)] \qquad (1)$$

Layer 3

$$\frac{\delta W_3}{\delta t}=\frac{1}{\theta_s D_3}[Q_{2,3}-Q_3]$$

Wi	=	the change in volume of water existing in the ith layer,
s	=	the moisture content of the soil at 100% saturation,
t	=	the change in time,
D_i	=	the thickness of the soil layer,
Q_{ij}	=	the flow between layers,
s	=	the volumetric soil moisture at saturation for the given soil type,
x	=	the slope of the terrain defined by the term x
E_1	=	the rate of evaporation of the canopy, ground cover, and surface,
E_2	=	the rate of evaporation caused by the root structure and undergrowth,
P	=	the difference in the precipitation and the canopy evaporation and runoff.

The precipitation data used in this study was archived from weather collection. The combination of these two equations gives the historic soil strength data required to forecast soil strength changes with time. Equation 2 gives the relationship between soil strength and moisture content where the empircal constants are defined by Morris P.A. (1994)

$$Soil\ Strength=\exp^{(\alpha-\beta(\ln(MC\%)))} \qquad (2)$$

Where,

Soil Strength	=	cone index readings recorded on a WES cone penetrometer,
MC%	=	moisture content of the soil in percent,
α,β	=	empirical coefficients used to define relationships between cone index and moisture content.

IMPLEMENTATION OF THE MODEL

To demonstrate how an analyst would forecast soil strength using historic data, this study selects a region (Fort Lewis, Washington State) and the information necessary to compute soil strength over a ten-year period. The rainfall and evaporation data is downloaded from CDROM,

archived from local weather stations, and the terrain data defining slope, soil type, and vegetation is taken from the Defense Mapping Agency data base.

The historic soil strength data is used to define the coefficients necessary to forecast changes in soil strength for the next two years (Figure 5). Mobility predictions are made for each soil strength forecast using the mobility model. The quickest route between two points on the map is selected based on the nominal forecast, the probability of immobilization is based on the minimum forecasted soil strength, and the variance in arrival times based on the difference between the minimum and maximum soil strength.

The Forecast Model. The term denotes a backward shift operator, indicating the terms $(1\text{-}X_t)$, while the coefficients indicating the sensitivity of the soil strength to past changes in soil strength are defined for each separate soil type. For the twelve different soil types considered in this study, the prediction model is given in the form of $(pdq)(PDQ)_{12}$. This was determined by considering correlations and autocorrelations given climatic conditions. The twelve-month seasonality indicates strong recurring cyclic trends each year, which can be identified with wet winters and dry summers. The coefficients will take a different form for a different regional area if climatic conditions change. Each soil type exhibits a first order polynomial based on the residual autocorrelation and partial autocorrelation plots; therefore, additional coefficients are not necessary to describe this forecasted time series.

The forecasted soil strength variation, for a Well Graded Sand (SW) in the Fort Lewis area, is given by a SARIMA model of order $(1,0,0)x(0,1,1)_{12}$, indicating a stationary time series model is provided by differencing the soil strength between the first and twelfth month. The appropriate Box-Jenkins model based on the observed correlations and autocorrelations of the time series is given by Equation 2 where $W_t = {}_{12}X_t$. Therefore, it can be shown that for the soil type described in Equation 2 for the Fort Lewis area, the soil strength at time t is dependent on the soil strength at time t-1,t-12, and t-13 as well as the innovation at time t-12. The coefficients in Table 1 are used to solve for Xt.

$$
\begin{aligned}
(1-\Phi B)(1-B^{12})X_t &= (1+\theta B^{12})Z_t \\
(1-B^{12}+\Phi B^{13}-\Phi B)X_t &= Z_t+\theta Z_{t-12} \\
X_t &= X_{t-12}-\Phi X_{t-13}+\Phi X_{t-1}-\theta Z_{t-12}+Z_t
\end{aligned}
\qquad (3)
$$

A Neural Network Approach. A neural network approach was employed in this study to forcast changes in soil strength. The data representing the daily soil strength was reprocessed by the use of a scaling factor. This scaling factor, shown in Equation 3, allows for faster convergence of the neural network. This technique created a set of data whose ranges were from 0 to 1.

$$
\frac{\textit{Soil Strength for Day } (i)}{\textit{Maximum Measured Soil Strength}} \qquad (4)
$$

The general architecture of the neural network is illustrated in Figure 4. The neural network was trained using a backpropagation technique. The details of the derivation of the backpropagation are

given by Hecht-Nielsen, R., 1990(7). The network was three-layered with the first layer having seven neurons. This first layer is the input layer using past daily measurements of soil strength. The first layer is fully connected to a second layer with three neurons and, finally, a third layer with one neuron. Each neuron had a sigmoid function of the type similar to the logistic response function. A training rate of 0.2 and a momentum factor of 0.5 were applied to each neuron during the backpropagation phase. Like the logistic response function, the output of the neural network fell between 0 and 1.

CONCLUSIONS

A forecasting procedure is proposed for temporal changes in soil strength to provide average, maximum and minimum conditions affecting the routing of vehicles. Specific conclusions drawn from this study are:

A Box-Jenkins approach a neural network approach to forecasting temporal soil strength were compared. The neural network approach provided a better match to the nonlinear trends of the time series data defining soil strength.

Correlations existed between daily and seasonal changes in soil strength, suggesting temporal analysis of soil strength for mobility forecasts.

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Multiscale Constitutive Theory with Traction for Swelling Soils

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Abstract

A three-scale theory of swelling porous media was developed. The colloid sized fraction and vicinal water (water next to the colloid) are considered on the microscale. Hybrid mixture theory was used to upscale the colloids with vicinal water to form mesoscale particles. The particles and bulk water (water next to the swelling particles) were then homogenized via two different techniques to form a swelling mixture of the macroscale. The solid phase on the macroscale can be viewed as a porous matrix consisting of swelling porous particles. Three Darcy-type laws were obtained on the macroscale, two corresponding to different bulk-water connectivities, and the third accounting for flow do to shear stress. The theory was used to construct a three-dimensional model of flow and consolidation in swelling soils under either normal load or shear stress.

The transport of moisture in shrinking colloids during drying was studied based on a novel thermomechanical theory developed previously by the authors. The drying theory accounts for a structural transition in the material during drying. This characteristic was accounted for using a term involving the non-equilibrium deformation viscosity in the equation governing moisture transport. The theory was applied to the drying of a model cylindrical colloidal system and the equations were solved using a lagrangian FD technique. The predicted drying characteristics depend on the Deborah number (a ratio of the characteristic relaxation time for matrix shrinkage and a characteristic diffusion time), the Biot number, and the newly defined Achanta number (ratio of the Deborah and Biot numbers). At intermediate and high Deborah numbers, drying is non-Darcian and gives rise to drying shut off and shell/crust formation. The model was verified with experimental data.

A CONTACT MECHANICS APPROACH TO THE SOIL-TIRE INTERACTION PROBLEM

Antoinette Tordesillas*

"The forces that move an earthbound vehicle over the ground are, in the last analysis, soil reaction forces. The engine serves only to generate these soil reactions by transmitting a certain mechanical energy to the running gear. Recognition of this fact makes the interaction between the soil and the running gear the key problem of theoretical soil-vehicle mechanics."

Wiendieck, 1968

Introduction

The physical process of interaction between soil and the vehicle's running gear (tire or track) is both a complex and multivariate phenomenon. Over the past five decades, a wealth of experimental data and theoretical models of this interaction have emerged, yet the central problem of determining the contact properties, i.e. *the area of contact between the vehicle's running gear and soil, and the stresses and deformations arising therein*, remains unresolved (Tijink et al., 1995). The measurement of contact properties is exceedingly difficult, since these cannot be observed nor measured directly without disturbing the state of the contact interface. In the literature to date, there has been no report of a technique for measuring the complete set of contact properties of either the soil-tire or soil-track interface at a useful level of accuracy. Thus, theoretical models of soil-tire or soil-track interaction which do not rely on *apriori* knowledge of the contact properties would be a significant advance. More importantly, it would help facilitate **the use of such models in practice**, specifically in the engineering areas of: vehicle dynamics for simulation and design, and assessments of vehicle-induced soil compaction for land management.

In terms of the soil-tire interaction process, there are in essence two immediate challenges in developing theoretical models of this process. The first is the mathematical formulation of the soil-tire contact problem, which accounts for the most influential parameters of the interaction. The second is the determination of the constitutive law which captures real soil behavior under vehicular loading. The work summarized herein addresses the first challenge. Specifically, a new approach to the analysis of the soil-tire interaction system which is based on the principles of contact mechanics is presented (Johnson, 1985). This methodology obviates the need to specify the contact properties *a priori*; instead the contact properties are solved for together with the internal states of the bodies based on more directly measurable quantities. This is distinct from prior methods which are based on the classical boundary value approach in which the contact properties serve as boundary conditions and thus must be specified at the outset: examples of such methods can be found in Pollock et al. (1986), Kirby (1989), Raper and Erbach (1990), and Saliba (1990). To demonstrate the contact mechanics approach, a soil-tire contact model is developed using simple constitutive laws: the tire is assumed to be linear elastic and the soil is assumed to be either linear elastic or linear viscoelastic. The ultimate purpose of this study is to serve as a prelude to the development of a network of contact mechanics based models in which more realistic constitutive laws for soil are implemented, thereby addressing the second challenge alluded to above.

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The soil-tire contact problem

As shown in Figure 1, the model consists of a cylinder (tire) in rolling contact over a half-space (soil). The cylinder moves at a constant velocity V in the x-direction, and is

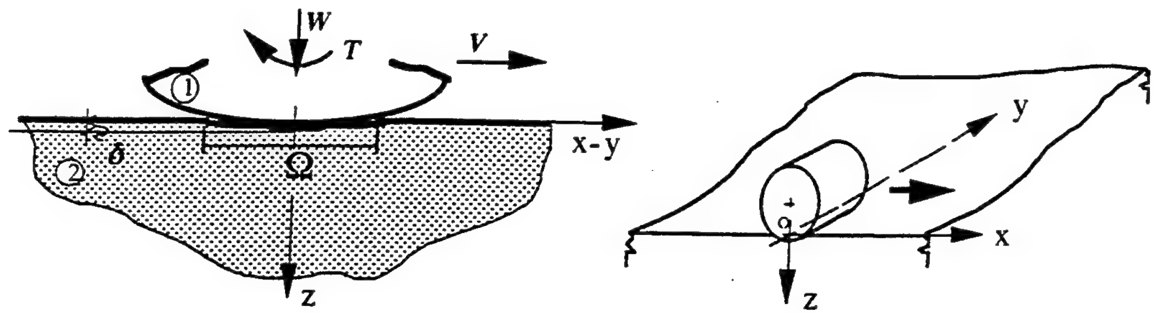

FIGURE 1: An elastic cylinder in rolling contact over a viscoelastic (or elastic) half-space.

subject to a vertical load W and torque T. Figure 2 illustrates the two configurations of contact: undeformed and deformed. An arbitrary pair of surface points with the same xy coordinates, which is referred to in the figure as corresponding points, is considered in both of these configurations. Let $h(x,y)$ denote the undeformed separation between such pair of surface points so that, after deformation, their separation becomes

$$u_z^{(1)}(x,y)+u_z^{(2)}(x,y)+h(x,y)-\delta,$$

$u_z^{(n)}$ denotes the displacement component in the z-direction of the point on the surface of body (n) n=1, 2; δ represents the relative approach of the bodies (i.e. the downward displacement of the tire axle into the soil). Accordingly, the laws governing the contact between the two deformable bodies may be stated as follows:

(a) The contacting bodies must not interpenetrate:

$$u_z^{(1)}(x,y)+u_z^{(2)}(x,y)+h(x,y)-\delta \begin{cases} =0, & (x,y)\in\Omega, \\ >0, & (x,y)\notin\Omega, \end{cases} \tag{1}$$

where Ω represents the contact area.

(b) Tensile stresses cannot be sustained within the contact area, hence the normal contact stress $p_N(x,y)$ must be compressive and zero outside Ω:

$$p_N(x,y) \begin{cases} >0, & (x,y)\in\Omega, \\ =0, & (x,y)\notin\Omega. \end{cases} \tag{2}$$

(c) The friction at the interface is assumed to obey Coulomb's law. Hence, a traction bound is imposed on the tangential stress $p_T(x,y)$, and a distinction is made between two regions of the contact area: that region which is under slip Ω_S and that which is under adhesion Ω_A ($\Omega_A+\Omega_S=\Omega$), i.e.

$$|p_N(x,y)| \begin{cases} <\mu p_T(x,y), & S=0, \quad (x,y)\in\Omega_A, \\ =\text{sign}(S)\mu p_T(x,y), & S\neq 0, \quad (x,y)\in\Omega_S, \end{cases} \tag{3}$$

where

$$S=(v^{(1)}-v^{(2)})-\frac{1}{2}(v^{(1)}+v^{(2)})\frac{\partial \hat{u}_x}{\partial x}, \quad \hat{u}_x=u_x^{(1)}-u_x^{(2)},$$

μ is the coefficient of friction, S denotes slip, $v^{(1)}$ and $v^{(2)}$ are the local velocities of bodies 1 and 2 respectively.

(d) The constitutive relation for body (n) enters into the displacement:

$$u_z^{(n)} = \iint F^{(n)}(x - x', y - y') p_z(x', y') dx'dy' \tag{4}$$

where $F^{(n)}(x - x', y - y')$ is known as the influence function and is defined as the displacement at (x, y) due to a unit point load acting at (x', y'), and $p_z(x', y')$ is the z-component of the contact stress at (x', y').

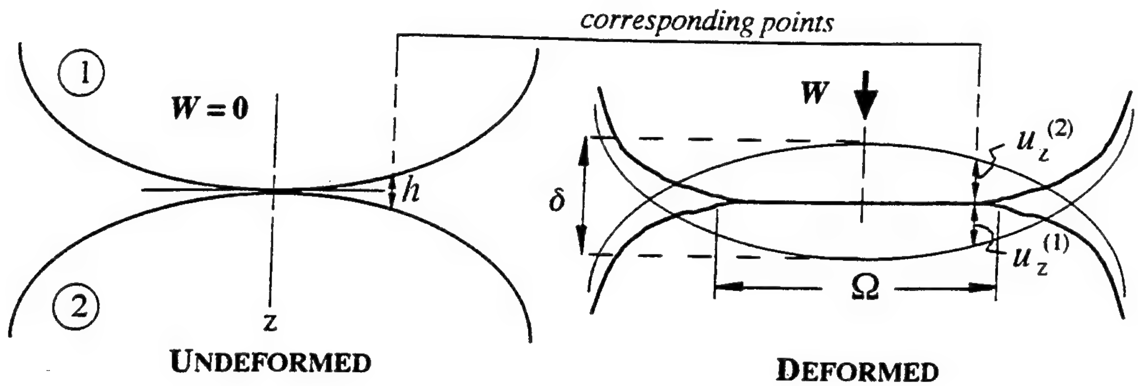

FIGURE 2. The contact of two deformable bodies, before and after deformation.

Solution Procedure

The model for the tire is a three-dimensional homogenous, isotropic, circular elastic cylinder with diameter and width equal to that of the pneumatic tire to be analyzed (see Figure 3). The classical Boussinesq-Cerruti stress-displacement relation for the elastic cylinder is used to evaluate the influence function $F^{(1)}$ in equation (4) (Johnson, 1985). On the other hand, the stress-displacement relation for the 3-parameter viscoelastic soil (i.e., Maxwell and Kelvin elements in series) is used to calculate the influence function $F^{(2)}$ (Kalker, 1990).

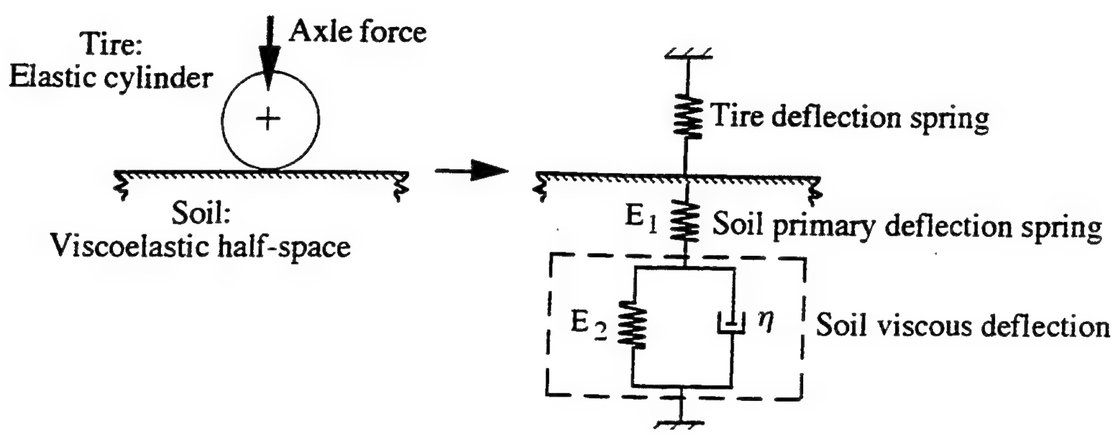

FIGURE 3. The soil-tire contact model.

The contact problem involves the determination of the normal and tangential stresses which satisfy the contact constraints stated in equations (1-3), both inside and outside the contact area Ω whose size and shape may not be known at the outset. This is solved using the method presented in Kalker (1988), in which the contact problem is transformed into an optimization problem. Specifically, the true contact area and contact stresses are those which minimize the complementary energy which is represented by the object function Φ, subject to the contact conditions in equations (1-3) which are represented by the equality and inequality constraints $\mathbf{f}(\mathbf{z}) = \mathbf{0}$ and $\mathbf{h}(\mathbf{z}) \geq \mathbf{0}$ respectively:

$$\underset{\mathbf{z}}{\mathit{Minimize}}\ \Phi(\mathbf{z})$$

$$\mathit{subject\ to}\quad \mathbf{f}(\mathbf{z}) = \mathbf{0} \text{ and } \mathbf{h}(\mathbf{z}) \geq \mathbf{0},$$

$\mathbf{z}$ is an n-dimension vector; Φ is a twice differentiable, strictly convex object function such that there exists a feasible point $\mathbf{z}^*$ with $\Phi(\mathbf{z}^*) < \infty$, while $\Phi(\mathbf{z}) \rightarrow \infty$ as $\mathbf{z}^T\mathbf{z} \rightarrow \infty$. This system can be rigorously solved using well developed techniques of nonlinear mathematical programming.

The discretization procedure is the same as that employed in Tordesillas and Hill (1991) in which a potential contact area is specified which must enclose the unknown true contact area. The potential contact area is then divided into small rectangular cells, each with constant stress P_I as shown in Figure 4. Thus, the overall contact stress distribution is discontinuous and piecewise constant. The contact area is the boundary between the regions in which $P_I > 0$ and $P_I = 0$, and is therefore defined to the accuracy of the cell size.

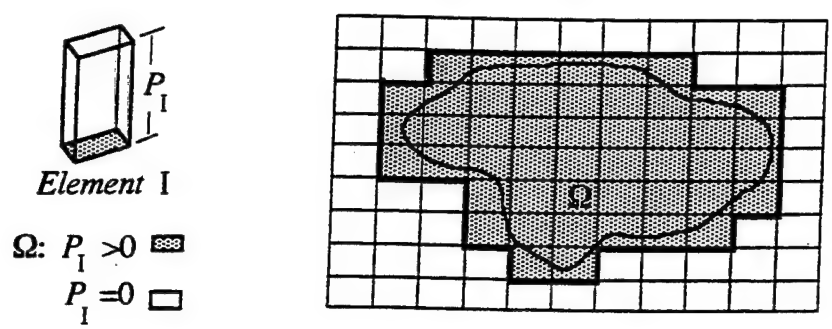

FIGURE 4. True contact area –; Predicted contact area from the soil-tire contact model —.

Table 1 presents a list of the input parameters for the soil-tire contact model. Input properties listed as I.1 enter into the stress-displacement relation $F^{(1)}$ in equation 4. These input values are available from the tire manufacturer. The emphasis here is to incorporate the basic elastic behavior and geometry of the tire under the given operating conditions. Specifically, the effective Young's elastic modulus must be as close as possible to that of the pneumatic tire, and reflect *both* its inflation pressure and carcass stiffness or strength. To incorporate tread curvature, the cylindrical tire model can vary in radius along the transverse direction. Input I.2 constitute the soil properties which enter into $F^{(2)}$ in equation 4. Table 2 lists the contact properties determined by the soil-tire contact model. Details of this entire study and its results will be presented in an upcoming publication.

TABLE 1: INPUT parameters required for the soil-tire contact model

I.1 TIRE PROPERTIES	I.2 SOIL PROPERTIES	I.3 OPERATIONAL VARIABLES
– overall tire radius	– Young's elastic modulus for the Maxwell spring	– vertical axle load
– transverse radius	– Young's elastic modulus for the Kelvin element	– friction coefficient at the soil-tire interface, static and dynamic
– Young's elastic modulus	– dashpot viscosity coefficient for the Kelvin element	– traveling velocity of the tire
– Poisson's ratio (of tread rubber)	– Poisson's ratio	– angular velocity of the tire

TABLE 2: OUTPUT parameters of the soil-tire contact model

– tire axle displacement and sinkage
– contact area
– contact stresses (normal and tangential)
– contact displacements (normal and tangential)

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Landfill Compaction Model

L. Chi[1]

Abstract

A Finite Element (FE) based 3–D nonlinear dynamic compaction model was developed at Caterpillar for use with landfill and soil compaction equipment. The model, built by using ABAQUS/Explicit, simulates one or more rigid wheels rolling on a deformable, plastic soil. Model inputs include wheel size, wheel load, wheel velocities, and a material model for soil. The model predicts the soil deformation, density change, dynamic wheel sinkage, rut depth, soil stress distribution, contact pressure and relative motion at the soil–wheel interface, and pull and torque on the wheel center. Model verification showed that the soil material model accurately reproduced elastic rebound and permanent plastic deformation obtained from field tests. The compaction model also resulted in close predictions of dynamic sinkage, resultant pull and torque on the wheel measured in soilbin test. Simulation results demonstrated that the model is capable of predicting the effects of multiple wheel passes, different wheel load–size combinations, various lift thicknesses of uncompacted layers. The model also predicted some interesting results of pressure distribution and relative motion at the soil–wheel interface. This model has been applied to evaluate new machine concepts and to compare current machine performance.

Introduction

Modeling machine mechanics has become an increasingly common practice in product design and development. Modeling the performance of an earthmoving machine requires not only a machine model but also a model for earth materials. In recent years, enormous efforts have been made to model soil compaction problems. All models developed for soil compaction can be divided into two categories: conventional analytical methods based upon Boussinesq equations and numerical methods, e.g. finite element (FE) methods.

Earlier compaction models were developed based upon the Boussinesq equation [1–2]. This method first computes the soil stress states from the known contact area and contact pressure, and then back calculates soil volume change and soil deformation. Advantages of this method are easy to use and less demanding on computing power and time. However, the method have a number of drawbacks and limitations due to the assumptions made in Boussinesq equations [2–3]. This model can be used as a useful tool for education and extension purpose[3], but is not adequate to accurately predict the performance of a real machine.

Invention of more powerful computers and the development of more advanced soil constitutive models made the FE technique a feasible method to model soil compaction. A number of axisymmetric FE compaction models were developed [4–6]. Raper et al. [7] showed that the FE prediction of soil stresses compared well to laboratory test results. Chi et al. [8] developed a 3–D

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nonlinear FE compaction model and model prediction of soil density compacted well to the field test results. However, all the above models still required contact area and contact pressure as model inputs. These contact characteristics are dependant on the type of running gears and terrain properties, and their relationships are very complicated and difficult to determine.

The recent development in modeling contact problems has made it is possible to model the soil–wheel interface in the FE analysis. This paper reported a new compaction model which included compaction wheels as part of the model. This model used wheel load and wheel geometry as model inputs in stead of the contact area and pressure. Beside predicting soil volume change and deformation, the model also calculates the wheel torque, wheel pull, contact pressure, and relative motion at the soil–wheel interface.

Model Description

This compaction model is essentially a three–dimensional, dynamic, nonlinear finite FE model built by using ABAQUS/Explicit. The model consists of two main parts: a deformable soil mesh and one or more rigid wheel meshes. The rigid wheel carries a certain vertical load and rolls on the soil surface with controlled motion pattern. Soil mesh was further divided into two parts: loose, uncompacted top soil and dense, pre–compacted base. Drucker–Prager's cap model [9] was used for the top soil, while a simple elastic model was used for the base soil.

Interaction between the wheel surface and soil surface was modeled by a friction type contact formulation. A high friction of coefficient was used to include effects of both friction between drum surface and soil, and the tips. A master–slave contact surface interaction defined rigid wheel surface as master surface and soil surface as slave surface. Therefore, only nodal displacements on the soil surface were adjusted when overlapping of two surfaces was encountered at the soil–wheel interface.

Model inputs include wheel size, vertical load on the wheel, wheel rotary and/or linear velocities, wheel mass and rotation inertia, and soil mechanical properties. The model predicts the amount of soil density change, soil compaction profile under the wheel, required pull and torque, and the contact pressure and shear stress at the soil–wheel interface.

Verification of Material Model

Drucker–Prager's cap model was used for the uncompacted soil and waste at the surface. This material model accounts for the effect of elastic rebound, shear and compression induced plastic deformations. There are several standardized test procedures for determining soil material parameters required by the Drucker–Prager cap model. However, material property tests for landfill materials become more complicated and require more specialized equipment. Aggregates' sizes of landfill materials are usually much larger than that of ordinary soil, silt or sand. Large size samples are required to minimize the effect of aggregates' sizes on test results.

Caterpillar has constructed a test device, called "waste crusher", for testing the compaction behavior of landfill materials in the field. Field tests were conducted at Green Valley landfill, Illinois, in September of 1993. Field test results showed several important characteristics of landfill materials.

First, The field test results showed that the elastic stiffness of the landfill material increased as load or its density increased. A variable Young's modulus is required to correctly reflect this nonlinear elastic behavior. Test results also showed that large plastic volume change occurred during compaction. In addition, the test data showed time delay behavior of the landfill material when a sudden load was applied or released.

The Drucker–Prager cap model in ABAQUS requires inputs of six model parameters (two elastic parameters, three failure parameters, and a constant eccentricity for the cap yield surface) and a cap hardening curve (data set). Elastic Young's modulus and Poisson's ratio were determined from the rebound characteristics of the filed tests. The cap hardening curve was calculated from the permanent volume changes under different loads obtained from the field test results. The soil model also used a typical cohesion and internal friction values [10–11] for soil failure surface. One element mesh was used to verify the soil material model against field test results. Figure 1 showed that the soil model accurately predicted elastic rebound and permanent volume change under different loads.

Verification of Compaction Model to Soil Bin Tests

Validation of modeling effect of the soil–wheel interaction required soil bin compaction tests. Soil bin test used a scaled model of compaction roller on a well controlled artificial soil. The vertical load, pull, torque, roller sinkage, rotary and linear speeds were recorded in the test.

Parameters and the cap work hardening curve for this artificial soil were determined from triaxial compression test results and one–dimensional consolidation test results conducted by Civil Engineering Department, UIUC. Similar to the material model for landfill waste, Drucker–Prager's cap model accurate reproduced the stress–strain curve for one–dimensional consolidation test.

A 3D compaction model was built to verify soil bin tests. The model used measured vertical load, linear and rotary velocities of compaction wheel as model input and predicted the wheel sinkage, wheel torque and pull. The initial soil density in the soil bin was lower than the densities of soil specimen used for one–dimensional consolidation tests. As a result, the cap hardening curve and soil cohesion were adjusted. A smooth curve was used at the beginning of the cap hardening relationship because of lacking of some plastic strain data at low stress. Results showed a close prediction of dynamic roller sinkage (Figure 2). The model predicted the same trends of accumulated compaction by repeated roller passes. Some over–prediction of roller sinkage at the first pass could be caused by the lack of test data in cap hardening curve at low stress. The model accurately predicted pull and torque when the roller rotary and linear speeds reached relative stable states (Figures 3 and 4). Oscillations in vertical load, roller and cart speeds were recorded at transition periods between each pass. As these signals were used as model inputs, oscillation was also found in predicted pull and torque during the transition periods. Soil acted as a soft media, which can damp out some dynamic oscillation in the force. Therefore, both measured and predicted roller sinkage showed less oscillation than measured and predicted forces on the roller.

Model Predictions

The compaction model used average final density of the central elements of uncompacted loose layer to quantify the degree of compaction. The model was used to simulate the performance of real

machines. Results showed that the model predicted correct trends of the effects of the wheel size, wheel load, wheel slip and lift thicknesses. Results also demonstrated that the compaction model is capable of predicting additional density increase under repeated wheel passes. The model prediction of density change compared well to the previous field test results.

Compaction profile under the wheel can be obtained by the contour plot of void ratio calculated by FE analysis. The results showed that, after first wheel pass, soil stiffness at the surface increased. As a result, the contact area for the second wheel pass was smaller and additional soil compaction was produced by the high contact pressure. Simulation results also showed that a hard soil layer was formed at the surface during first and second wheel passes. Further wheel passes tend to compact soil to lower sub–layers.

The compaction model also calculate the wheel torque and pull and then the wheel power can be estimated. Landfill compactors usually have a slightly smaller vertical load on the front axle than that on the rear axle. It was found that, during the first machine pass, both front and rear wheel passes resulted in significant compaction. As a result, both front and rear wheels required high torques. For the second and the third machine passes, the front wheels resulted in little soil compaction and thus required less torque than the rear wheels. The model predicted that total wheel power required for the second and third machine passes was significantly less than that for the first machine pass if the horizontal force from blade was neglected. The wheel power predicted also increased with the lift thickness of uncompacted layer.

Future Studies on Compaction Model

At current time, one obstacle in improving the accuracy of model prediction is still the available computing power. The soil mesh in current model was generated to limit the total simulation time within 24 hr on a HP 700 series workstation. Much finer mesh will be required if more detailed wheel geometry, such as tips and grousers, are included in the model. Latest development in parallel system structure, such as SGI's Power Challenge Array, showed some promise on dramatic increase in the computer speed with relatively low cost. However, at this stage of development, Abaqus code has not been efficiently optimized for this parallel system structure. The reduction in computing time by using multiple processor is not significant, especially for nonlinear plastic and contact problems [12]. The current cost/performance ratio of multiple processors is much higher than that of a single processor.

Constitutive model of soil material directly affects the model accuracy. No one of material models currently available for soils included all the mechanical behaviors of the soil. There is still a need to develop constitutive model for soil and other granular materials, and to code the model for various numerical simulations.

The current compaction model uses rigid wheels to model compaction device. A future of model development will include deformable rubber tires. The model combining deformable tires and deformable soil body will become more complicated and require much more computing power. This tire mobility model will require compatible models of rubber tires and the soil mass.

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Figure 1. Verification of the material model for landfill waste.

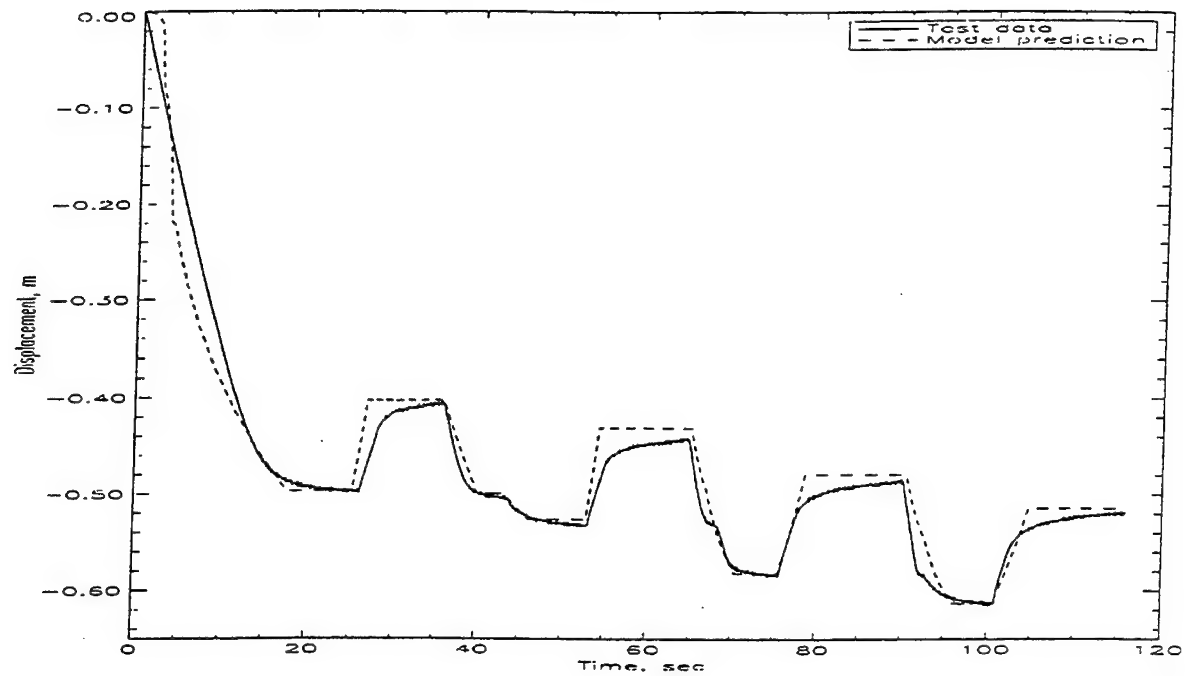


Figure 2. Model prediction of dynamic roller sinkage.

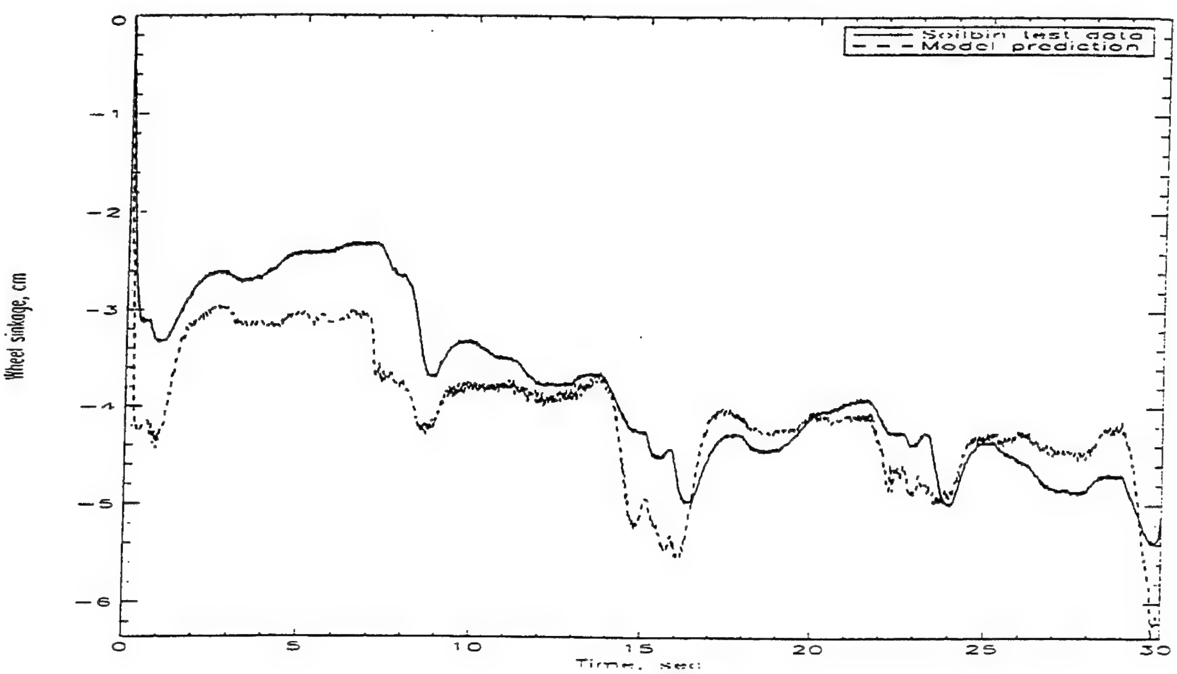


Figure 3. Model prediction of pull on roller

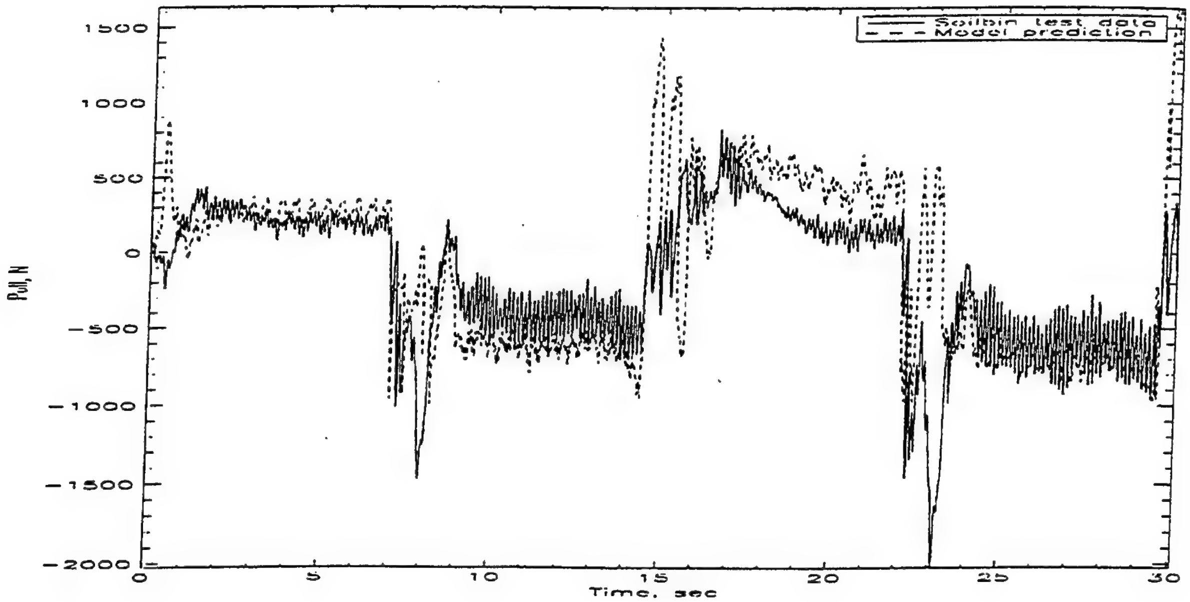
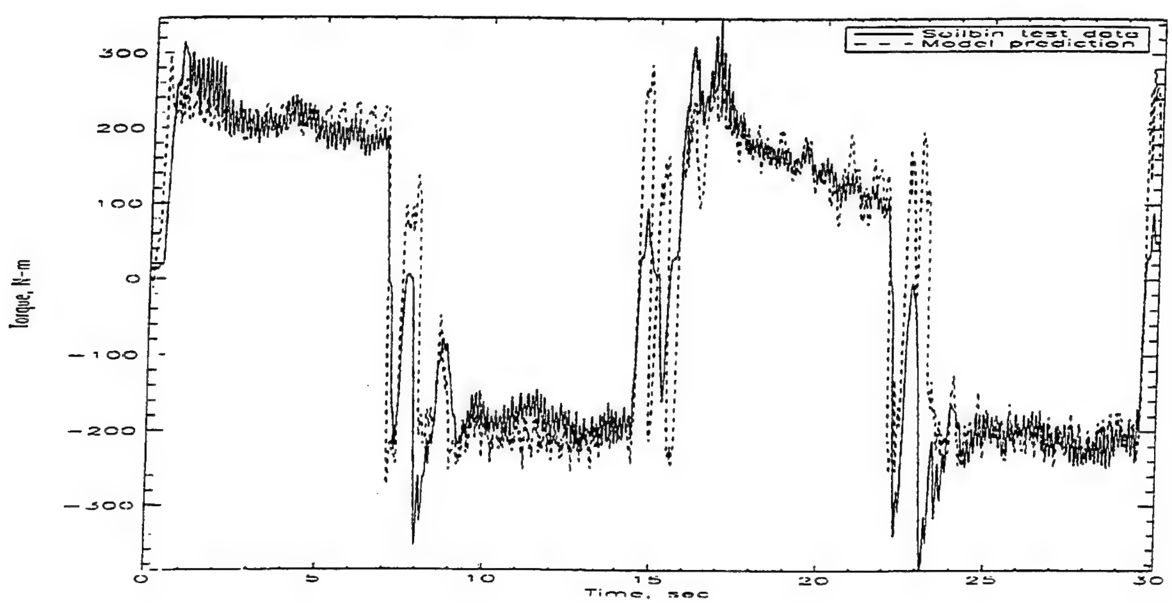


Figure 4. Model prediction of torque on roller.



Vehicle-Terrain Problems Potentially Addressable by Particle Dynamics Modeling

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ABSTRACT

Particle Dynamics Models (PDM) have found utility in previous studies of stress-strain relations and identification of failure modes associated with terrain-vehicle interaction. In PDM the motion of individual soil or other terrain particles is followed by explicitly solving the Newtonian equations of motion for each particle. Generally, these models have been restricted to 2 dimensions and to circular particles. We will discuss the potential utility of such models for studies of noncircular particles, for three dimensional studies, for studies in which cohesion between particles is present, for studies where interstitial water is important, for modeling large, discrete objects such as boulders, and for modeling objects constructed from non-geological materials.

Introduction

In the PDM method, the forces acting on individual particles are computed, and the Newtonian equations of motion solved to give the detailed motion of the particles through time. Systems comprised of tens of thousands of particles can be studied in this way. Applications include the motion of sand grains in the wind, the transport of sediment by flowing water in the bottom of a stream, the descent of a rockfall down a mountainside, the reaction of soil particles to applied stresses, the collapse of engineered structures, and so on. For each application one must determine the size of the particles to be used in the simulation, the particle shape, the particle mechanical properties, and the nature of the forces that act upon the particle.

Most applications to date have made use of spherical grains, or, more often, of circular grains in two-dimensions. The minimal number of forces acting on a given grain include the particle weight, and the contact forces between the particles. In most implementations of PDM, the forces at a grain contact are modeled by a stiff, damped normal spring and a tangential frictional force. The stiff spring is a surrogate for the actual elastic dynamics of the contact event. The spring is chosen to be stiff enough that significant

particle overlap does not occur. Elastic contact between grains is describable by a nonlinear Hertzian "spring". However in most applications the grain-grain contact forces far exceed the elastic limit of the grain material. It often suffices to use, then, a linear spring, with a velocity dependent damping term that can account in an approximate way for the nonelastic aspects of the collision.

The tangential force is often modeled by a stiff tangential spring that keeps two contacting particles from slipping past one another. Slip can be implemented by invoking a Coulomb-type friction law, so that if the applied shear force exceeds a nominal value related to the normal force and a friction coefficient, then the tangential spring is released and replaced by the product of the normal force and the friction coefficient.

In this simple picture, three equations of motion are required to describe the motion of particles in two dimensions, namely those involving the x and y components of force, and the torque equation that specifies the angular acceleration.

Some impression of the calculational power needed to implement PDM can be gained by noting that (in 2 dimensions) the normal and tangential forces must be broken down into x and y components, for a total of 2 second order or 4 first order differential equations for each particle. The rotational degree of freedom adds another second order or two first order equations, for a total of 6 first order differential equations per particle. For a system of 10,000 particles, approximately 60,000 equations need to be iterated at each time step.

A second calculational challenge is contact detection, deciding whether any two particles are touching or not. If the separation between every two particles is checked at every time step, the time spent in contact detection increases like the square of the number N of particles in the system. This problem is usually avoided by implementing a fine-graining strategy of some kind. One approach is to use a neighbor list, in which each particle carries a list of all its most recent neighbors. There are n particles on the neighbor list, and n<<N. Thus the time spent checking for contacts is proportional to anN+bN*2, where a and b are constants, and b is small. The bN*2 term reflects the fact that occasionally all particle contacts must be checked in order to update the neighbor lists.

<u>Three dimensions</u>

The number of equations to be solved increases from 3 second order equations to 6 second order equations - an additional translational degree of freedom plus two additional rotational degrees of freedom (for a total of three Euler angles or four quaternions). In going to 3 dimensions, the number of contacts per grain increases in most problems (by perhaps 50% to 100%). The increase in the number of contacts increases the number of force terms appearing in each equation to a total of perhaps 25 (for example, 6 contacts per grain with normal and tangential force contributions at each contact and the

corresponding normal and tangential damping forces, plus the particle weight.)

A more severe penalty in going to three dimensions is the increase in the surface-to-volume ratio. In two dimensions, 10000 particles arranged in a square contains approximately 400 particles on the boundary, and 9600 in the interior, for a surface-to-volume ration of 0.04. The same 10000 particle arranged into a cube have a surface-to-volume ratio of approximately 0.39, so that "edge effects" can be expected to be considerably greater in 3D than in 2D calculations, for the same number of particles.

<u>Particle Shape</u>

Most simulations to date have been performed with either circular particles in 2D, or spherical particles in 3D. This is mainly due to the ease of contact detection with such objects. An relatively easy way to relax the restriction to spherical particles, while retaining some simplicity in contact detection, is to construct nonspherical particles as overlapping composites of spherical subparticles. Each composite particle still satisfies its own equation of motion. Program logic is only slightly affected. In many problems involving geologic materials, particle shapes can be complex, and the use of nonspherical shapes may be desirable. The "composite overlap" method cannot produce particles with sharp edges, corners or points. Also, a set of 5000 nonspherical particles each composed of two spheres carries the calculational overhead of 10,000 noncomposite particles, so there is a limit to how complicated such composite particles can be made if one still wishes to simulate a large number of actual particles.

<u>Cohesion</u>

In some applications one may wish to simulate the behavior of a particulate system in which there is cohesion between particles - as in many soils for example. This can be accomplished within the PDM framework by adding an attractive component to the normal spring. The spring is set to "break" when it is stretched too far, indicating that at that point in the system the stresses have exceeded local tensional strength of the material. Fracture of brittle material can also be studied in this way, as well as the yielding behavior of plastic solids.

<u>Interstitial Fluids</u>

In some applications, such as those occurring in many types of sediment transport, a fluid is present, in addition to the grains. Where there is relative motion of grains and fluid, or where fluid pressures build up, fluid forces are exerted on the grains. Conversely, grain motion tends to transfer momentum to the fluid, affecting its state of motion. Where most grain-fluid interaction occurs along an interface with the particle system, as in bedload transport in a stream, a term can be added to the fluid equation of motion that represents the sink of momentum transferred to accelerated grains.

Likewise, via momentum conservation, a force can be added to the grain equation of motion that represents the drag force of the fluid on the particle. By explicitly conserving momentum, entrainment of grains from the bed has an immediate retarding effect on the near surface flow, which provides a built in moderating mechanism leading to an intrinsic transport capacity of the flow. This method has worked well in the study of certain aeolian and aqueous sediment transport problems.

The simulation of saturated granular media presents another challenge. During deformation of saturated granular media, an individual pore may either increase or decrease in volume. A decrease in pore volume at a particular site must be accommodated by an increase in pore volume elsewhere in the system, or by a change in the elevation of the water surface. As the volume of a pore is decreased, due to motion of the grains that define that pore, increased pore pressure generates a flow of fluid out of that pore into neighboring pore space. This flow is driven by the increased pressure in the original pore, and it is opposed by the flow resistance in the pore throat, and by the pressure differences between neighboring pores. As the granular material deforms, pore pressures will locally increase and decrease in response to statistically fluctuating pore volumes. Where pore pressures are elevated, grain-grain contact stresses will be relieved, and local deformation of the granular material can occur under relatively small applied stresses. Conversely, where pore pressure momentarily falls in response to deformation, grain-grain contact stresses can be expected to increase, and local deformation of the granular medium will be more difficult to achieve under the local instantaneous stress regime. Thus deformation rate can be expected to be influenced significantly by stochastic fluctuations of pore pressure. The practical consequence of this is that saturated granular material may be significantly weaker mechanically than the corresponding unsaturated material. This deformation-weakening mechanism has been advanced as a cause of the long run-out distances of some debris flows on alluvial fans. It may also be expected under some circumstances to be important in vehicle-terrain interaction on saturated soils. PDM methods represent one approach to the modeling of such systems.

<u>Large Objects</u>

While PDM models have been used largely to look at the dynamics of a systems of small particles (sand, gravel, soils), there is no inherent reason why the method cannot be applied to large particles such a cobbles or boulders, or even man-made objects such concrete debris. Rock fall debris at the bottom of a cliff, bouldery alluvial fan surfaces, outcrops of bedrock, and similar particle systems could be studied with PDM. PDM can be used to "construct" a potential traffic-surface by modeling natural formation processes - for example, by letting rocks tumble down a slope and come to rest at the bottom to form the terrain that must be trafficked. PDM can also be used to study stresses on and displacements of individual surface objects due

to the passing of vehicles, as well as the counter-forces exerted on the vehicle.

Non-geological materials

Application of PDM need not be restricted to the study of geologic materials such as soil grains and boulders. PDM "particles" could be constructed to represent objects such as tree trunks and steel beams. The dynamical interaction between such objects and moving vehicles can then be studied.

Video Tracking for Experimental Validation of Discrete Element Simulations of Large Discontinuous Deformations

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Abstract

The discrete element method (DEM) simulates large discontinuous deformations as a natural outcome of discrete particle interactions. The method is well suited for problems such as plowing, penetration, and hopper flows. However, verification of DEM simulations has been largely limited to comparisons with laboratory stress-strain diagrams of two dimensional simulations of a few thousand particles. This paper presents a three dimensional simulation of a laboratory plowing experiment in which a one-to-one correspondence is achieved between the number of particles and their size distribution in simulation and physical experiment. Particle displacement fields and velocities were obtained experimentally using automated video tracking and digital image analysis. The experiment and simulation agree closely both qualitatively and quantitatively.

Introduction

Many important problems in soil mechanics and particulate physics involve large discontinuous deformations which are beyond the capabilities of numerical simulations based on continuum mechanics. Examples are: soil plowing, penetrometers, pile driving, soil-tire interactions, hopper flows, mixing of powders, and mass movements by avalanche. In these problems, the soil may behave as a solid, a fluid, or as individual grains. Continuum formulations do not exist for such a wide range of behavior, particularly in the case of rate-independent friction materials such as sand [7].

The discrete element method (DEM) of Cundall and Strack [2] is well suited to particulate media because the soil is depicted as a discrete system. The kinematics of large deformation is inherent in the method and localized features such as shear bands emerge naturally from the behavior of

the assemblage. DEM models have been formulated for both two and three dimensional problems ([5] and [3]) and the feasibility of applying the method to practical engineering problems has been demonstrated [6]. However, experimental verification of DEM has largely relied on comparison of external boundary quantities, as in a laboratory triaxial test, where the strain field within the specimen is statistically homogeneous. Moreover, verification studies to date have involved only small two-dimensional particle assemblies (less than 10,000 particles). The boundary effects in such cases are large and the details at the particle-level become critical. This paper describes experimental verification of a large three dimensional DEM simulation for a problem with complex kinematics.

Description of Experiment

The studied problem was the horizontal translation of a vertical wall (or plow) through a uniform sand, as shown in Figure 1. The experiment was configured as a plane-strain test whereby motion of the wall was in one plane and the sand was confined between rigid glass plates. The simulation was three dimensional, in that, particles were free to move out-of-plane to the extent permitted by the boundaries. Comparison between simulation and experiment focused on sand deformation, velocity of individual points within the mass, and the plow force during advance. This particular problem was chosen for study because of the expected large deformations, development of shear bands and slope instability.

Description of DEM

A DEM model simulates the mechanical response of a particulate medium by explicitly accounting for the dynamics of each particle in the system. The acceleration of each particle is computed by dividing the net force caused by interactions among neighboring particles. Having found the acceleration, the particle's velocity and displacement are computed for a time step using explicit integration of Newton's laws of motion. At the end of each time step a search of the particulate space is made to compile a neighbors list for each particle. The updated neighbors list is then used to repeat the process for the next time step. The length of the time step is limited by a critical time step which depends on the natural frequency of the particle interaction and damping. If the computational time step exceeds the critical time step the computation becomes unstable.

The interaction forces between two particles represented by a damped spring in the normal direction and a spring in series with a frictional slider in the tangential (shear) direction. The normal force between the two particles, while loading, is computed as:

$$f^n = K^n \frac{R^A - R^B}{R^A + R^B} \tag{1}$$

where R^A and R^B are the radii of the two particles and K^n is the normal stiffness constant. During

unloading, a non-linear spring is used to create a hysteresis loop and thus dissipate energy. To this is added a viscous damper designed to cause the unloading phase of interaction to be critically damped. The intent of this damper design is to achieve significant energy dissipation without introducing spuriously large viscous effects into the constitutive relationship. Damper calibration is based on a coefficient of restitution $e = v_2/v_1$, where v_1 is the relative particle velocity prior to engaging the normal spring and v_2 is the velocity after the normal spring is disengaged.

To determine the shear force component of the particle-particle interaction, the tangential relative velocity is computed. The tangential relative velocity is integrated with respect to time to provide the relative tangential displacement for a computational time step:

$$\Delta\delta^s = V^s \Delta t. \tag{2}$$

The shear force increment for the time step is then computed as:

$$\Delta f^s = K^s \Delta\delta^s \tag{3}$$

where K^s is the shear stiffness constant. As long as the two particles remain in contact, the force increment is added to the total shear force from the previous time step, i. e.

$$f_N^s = f_{N-1}^s + \Delta\delta f^s \tag{4}$$

where the indices N and N-1 refer to times t_N and t_{N-1}, and $\Delta t = t_N - t_{N-1}$.

The magnitude of the shear force is compared to a maximum shear force allowed by the frictional slider. If the shear force exceeds this maximum frictional force, the shear force is set equal to the maximum value, as dictated by Coulomb theory:

$$f^s \leq f_{max}^s = f^n \tan\phi. \tag{5}$$

Once all forces acting on each particle have been determined, they are vector summed and the instantaneous acceleration is computed from the resultant. The particle accelerations are integrated over the current time step to obtain the updated velocity and the velocity is integrated over the current time step to obtain the updated location.

Modeling Approach and Validation

The key to applying DEM for prototype-scale simulations is to determine which particle-level processes must be captured accurately and which can be ignored. Comparisons of simulations and physical experiments are based on qualitative comparison of deformed shapes, quantitative comparison between simulated and measured load-displacement curves, and locations of shear bands.

These comparisons provide a means to assess the value of DEM as a practical engineering tool. The goal of the present study was to evaluate the ability of the DEM to simulate an experiment which is comparable with regard to particle size distribution, number of particles, problem dimensions, and loading rate. However, the simulated particles were spherical whereas the actual particles were well rounded but non-spherical. Also, because of limitations imposed by the explicit time integration scheme, particle stiffness was considerably smaller than that of the actual particles. Particle rotations were ignored.

Grain Size Distribution and Simulated Specimen Formation

The sand was modeled using 5 different particle sizes to represent the grain size distribution curve of Ottawa 20-30 sand. A conventional weight-based grain size distribution curve must be converted to a discrete probability distribution function represented by M different size particles. The probability of a particular grain diameter (as defined by standard sieve analysis) occurring in a sample is given by

$$P(D_x) = \frac{1}{D_x^3 \sum_{k=1}^{M} \frac{1}{D^3_{\frac{50(2k-1)}{M}}}}. \tag{6}$$

where x is the percent by weight smaller in diameter than D_x.

Equation (6) distributes the mass of solids equally among the M different sized particles.

The initial placement of particles closely follows the procedures used in the experiment. An initial soil fabric is obtained by first creating particles in accordance with equation (6). The particles are then randomly placed on a lattice with a spacing between centers large enough to minimize initial interparticle forces. The particles are then "rained" into the simulated rigid-wall container. The simulation continues until the particles achieve static equilibrium. The lateral constraint is then removed from the end of the simulated test box causing particles to run out creating a natural slope.

Simulation Description

The simulation consisted of 66,544 particles which corresponds to a nearly one-to-one correspondence between number of simulated and actual particles. The properties used for the simulation are shown in Table 1. As previously noted, the normal and shear spring stiffness were selected to keep the critical time step within feasible computational limits. The value used was in fact 8 orders of magnitude less than that estimated from elastic properties of the bulk particulate medium. Yet, penetration of contacts were approximately 9 percent of the particle diameter. While the low particle stiffness may not be suitable for study of particle-scale mechanisms or for dynamic

Table 1: Simulation Properties

Percent Passing:	Particle Sizes
10	.63 mm
30	.66 mm
50	.70 mm
70	.72 mm
90	.75 mm
Particle Shape	spherical
Specific Gravity	2.65
Contact Stiffness:	
Normal	1.4 kg/m
Shear	0.4 kg/m
Contact Friction Angle	15 degrees
Particle to Wall Friction	20 degrees
Coefficient of Restitution	0.04
Plow Advance	2.5 cm/sec
Time Step	2.E-5 sec

computations where wave propagation speeds are important, the authors have found that particle stiffness has limited effect on large flow-like deformation for which DEM is well suited.

To reduce the size of data files and to depict discrete particle data as continuum field variables (e.g., density, velocity and velocity gradients, and stresses), data were mapped to a grid as weighted averages. The weighting kernel consisted the same bi-linear basis function typically used for finite element interpolation. Spatial gradients were computed using the derivative of the smoothing kernel as a weighting function. After smoothed averages are computed for each grid location, data visualization is accomplished using standard finite element post processing software.

Experimental Verification

The physical model is shown in Figure 2. It consists of a rectangular vessel (300 mm in length $\times$ 150 mm in height $\times$ 8.5 mm in width) with transparent glass sides. However, only a portion of the vessel was used in the present study providing test dimensions as shown in Figure 1. The plow is attached to the underside of a small, four-wheeled trolley which travels along two rails. Sand is placed in the vessel using a deep-throated funnel. After the sand is placed to the desired height, the left endwall of the vessel is removed, thereby allowing the sand to flow out and form a slope at the soil's angle of repose. As the plow advances toward this wall sand can run out of the vessel. Thus, a nearly constant slope angle is maintained. The trolley is displaced at a constant rate of 2.5 cm/sec. A 250 gram-force load cell records the force on the plow during displacement.

Image Analysis Using the Particle Tracer

Video images of these plowing experiments were recorded in real time and analyzed using a computer vision system. An image processing and analysis program called "Particle Tracer" [4] semi-automatically obtained the shape of the sand surface and location of the plow with time, and the displacement trajectories of selected sand particles during plow advance.

To characterize the displacement field, individual sand particles are coated with a fluorescent dye. The experiment is recorded on video under UV light. The bright fluorescent tracer particles (see Figure 3) can be segmented from the other particles in the digitized images using a simple thresholding operation. All pixels with a grayscale value greater than some threshold value are marked as foreground regions and their grayscale pixel value is set equal to 255 (white). All other pixels are marked as black (grayscale value = 0).

The trajectory of the tracer particles is determined over a desired time interval by selecting the appropriate number of image frames to operate on. The initial image in the video sequence is read into the computer's memory and the tracer particles are segmented by thresholding. The particles in the second image are then segmented. A logical, unary "OR" operator is applied to these two images to produce a composite image. The "OR" operator yields a foreground pixel

value (indicating the presence of a tracer particle) if the pixel value in either of the "OR'd" images at the same pixel location is equal to 255. The third image is thresholded and "OR'd" with the previous composite. The process is repeated on all images in the desired time interval. The resulting "trace image" is essentially a digital time-lapse of the trajectories of the tracer particles over the corresponding time interval. Finally, the traces in the composite image are eroded using a thinning operator which removes the boundary pixels of each trace until all that remains is its skeleton. The "thinned" traces approximate the trajectory of the center of gravity of each of the tracer particles.

The user must select the number of frames to be operated on such that none of the particle traces overlap or intersect in the trace image. If the traces intersect, the program presently cannot distinguish the individual traces and they are labeled as a single trace. Also, if a tracer particle moves a distance greater than its diameter in successive image frames, gaps in the particle trace are produced. This can be corrected by increasing the size of the foreground regions in the thresholded images using a dilational morphological operator (essentially the opposite of the thinning operator) before "OR'ing" the images. In essence, the particle boundary is uniformly expanded outward until the previously disconnected traces merge.

The last grayscale image in each trace also serves as the first image of the next trace. This is done so that the particle traces overlap slightly between consecutive trace images and thus provide trace continuity from interval to interval.

In addition to providing the locations of the center of gravity of each tracer particle in each image frame in the entire video sequence, Tracer also determines the displacement magnitude and direction of the tracer particles, and thus, quantifies the displacement field.

In the present study, the plow was coated with the same fluorescent dye as the tracer particles and a white background was used behind the vessel as shown in Figure 3. This enables Tracer to also determine the soil surface profile and the location of the plow in each image.

Comparison of Results

The simulated test results are compared to the physical experiments in Figures 4 and 5 at 1 cm and 2 cm of plow advance respectively. The top figures (a), show the DEM simulation. Since, the individual particles are too numerous to be shown, the color spectrum represents "weighted mass densities", or equivalently, local porosities. The yellow areas reflect areas of lower mass density than the red.

One can see that two distinct regions of lower mass density have developed. Namely, at the slope surface, where shear banding and dilation during slope formation has occurred and in the mounded region ahead of the plow. Conversely, an area of relatively higher grain packing develops at the base of the plow where soil is confined and being compressed. The lines running from the tip of the plow to the toe of the mounded sand are velocity contours in cm/s. In the region to the left and below of the 1.0 cm/s contour, the particles are still essentially stationary. In the area

ahead of the top of the plow, the sand is moving as a rigid plug ahead of the advancing plow. Most importantly, the location of the shear band is easily identified by the closely spaced velocity contours.

Figures 4(b) and 5(b) show a snapshot of the physical experiment at plow displacements of 1.0 cm and 2.0 cm. The same build-up of a mound ahead of the advancing plow is observed. Interestingly, a video tape of the experiment gives the erroneous illusion that soil ahead of the plow is rolling-up counter-clockwise ahead of the advancing plow.

The true displacement field is revealed by the traces of the individual particles for the displacement increments 0.75 to 1.00 cm (Figure 4c) and 1.75 to 2.00 cm (Figure 5c). The lengths of the displacement vectors correspond to the incremental particle velocities. The contoured velocities are shown in Figures 4(d) and 5(d). The location of these contours is virtually identical to those of the DEM numerical simulations, indicating that the DEM has predicted the location, the width, and the motion of particles in the shear band with a high level of precision.

Conclusions

A detailed comparison was made between a laboratory experiment involving very large discontinuous deformation in sand and a simulated test using a large-scale DEM computation. The magnitude of the simulation provides a unique opportunity to assess the validity of the DEM based on experimental results. The simulation size captures the behavior of a particulate "continuum" while the small scale test permits a one-to-one correspondence between particle gradation in the simulation and the test. The close agreement between experiment and simulation indicates that many fine-grained details not captured by the simplistic particle interaction model are not relevant in statistically large assemblies.

This simulation represents the present limiting scale at which DEM can be used on a one-to-one basis. Even with improved computing hardware and technique, simulation capacity can be increased by only factors of 10 or 100. Such increases still do not translate into appreciably larger physical experiments. Yet it has been demonstrated that a middle ground does exist between computationally feasible DEM simulations and small-scale experiments that are applicable to engineering scale problems.

Acknowledgments

Experimental work on automated video tracking is funded by the Army Research Office under grant no. DAA404-95-1-0227 The equipment was purchased under Air Force Office of Scientific Research (AFOSR) grant no. F49620-92-0216. Mr. Scott Raschke's work is partially supported by AFOSR grant F49620-93-1-0406. The computer simulations and the resulting data presented herein, unless otherwise noted were obtained from research conducted under the MILITARY RESEARCH

DEVELOPMENT TEST AND EVALUATION PROGRAM of the United States Army Corps of Engineers by the U.S. Army Engineer Waterways Experiment Station. Permission is granted by the Chief of Engineers for publication of this paper.

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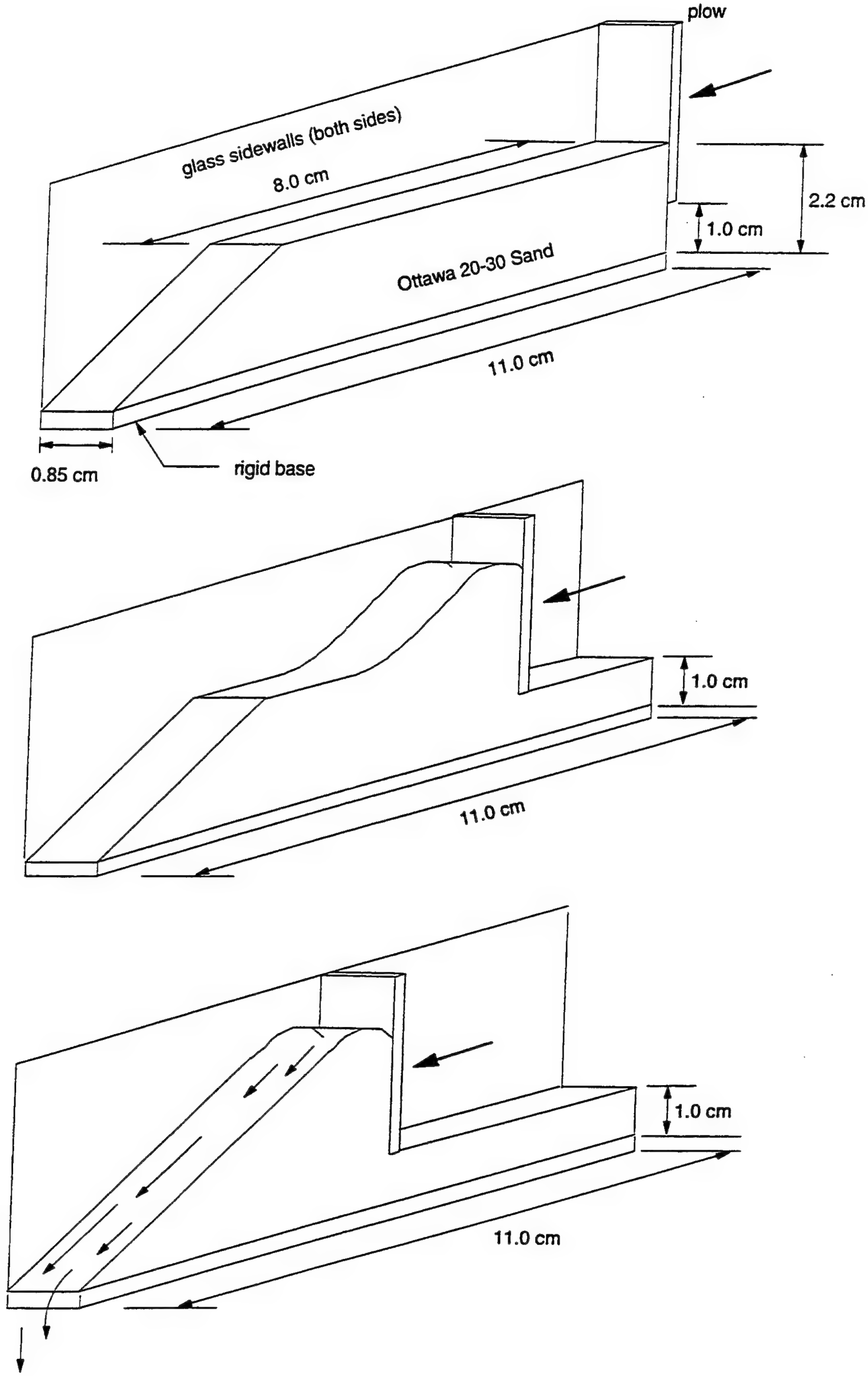
List of Figures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glass sidewalls (both sides)
8.0 cm
2.2 cm
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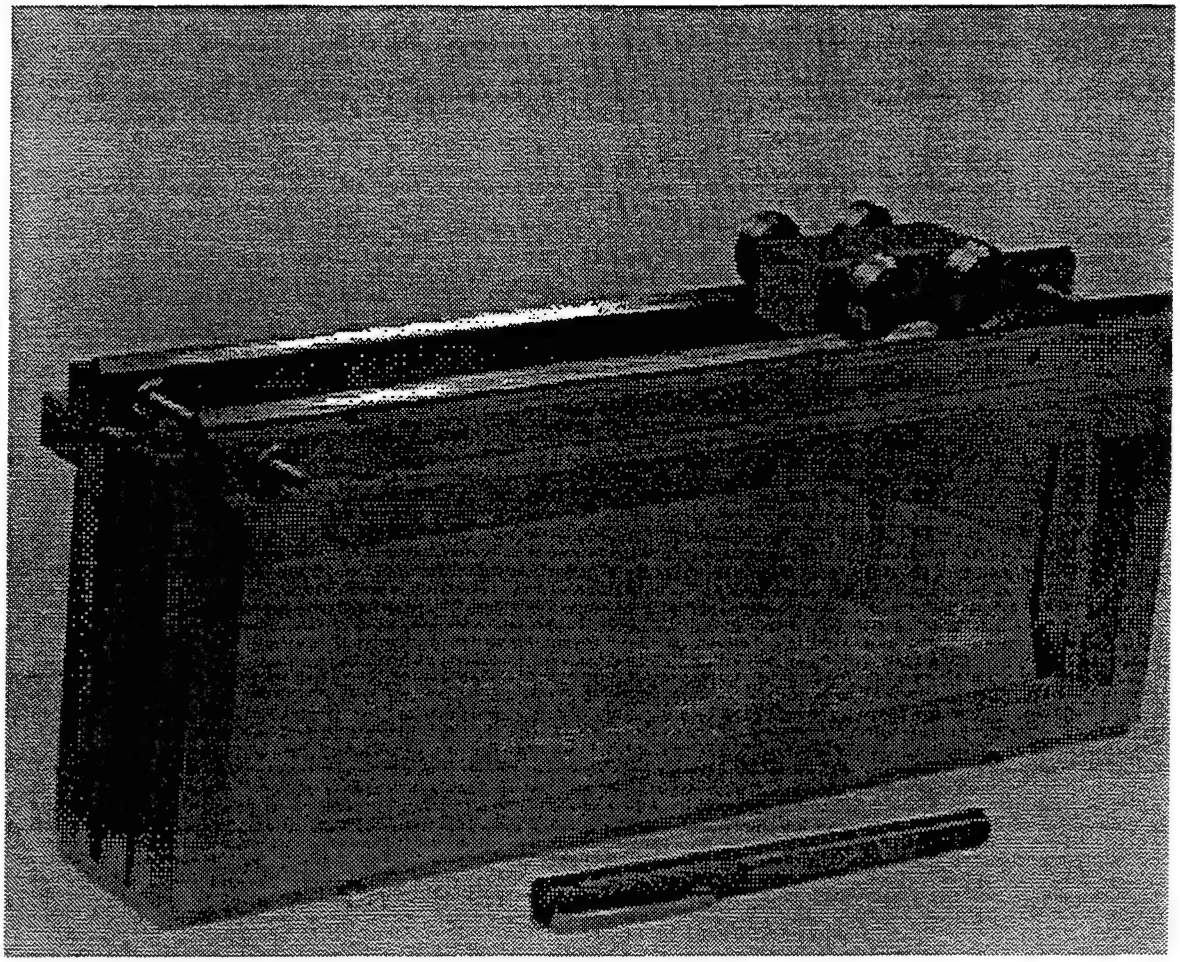
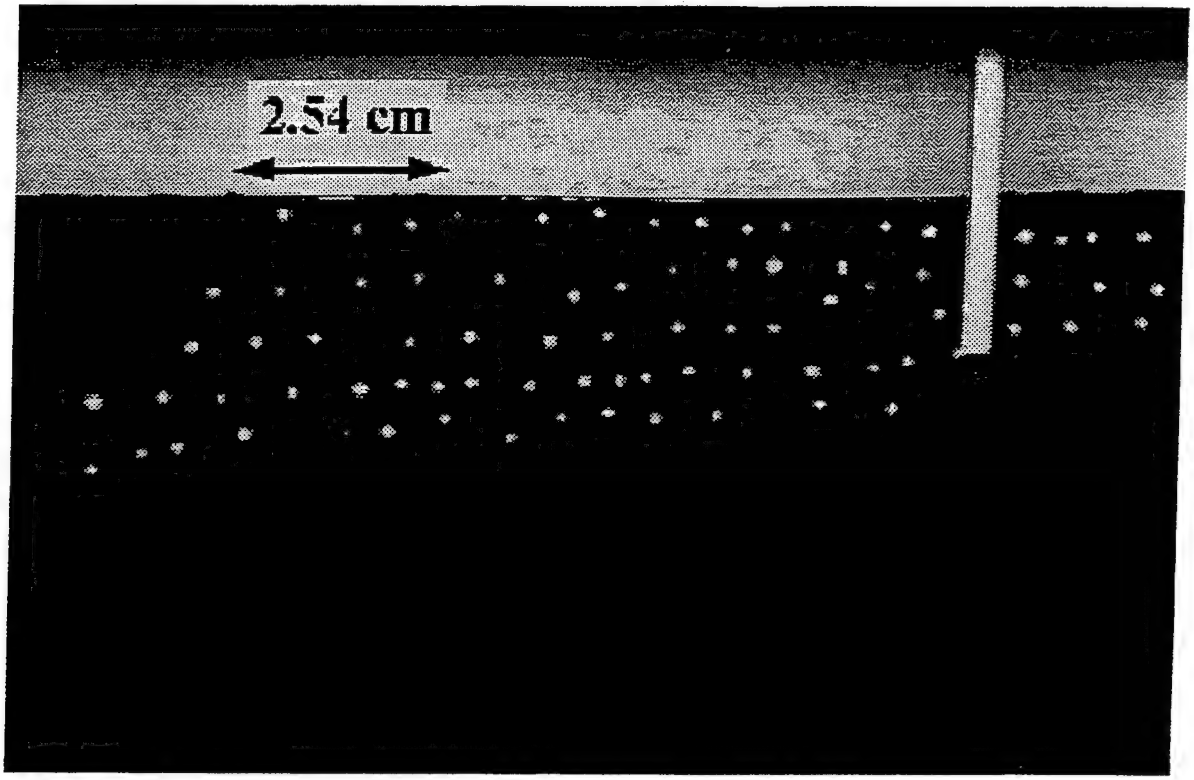
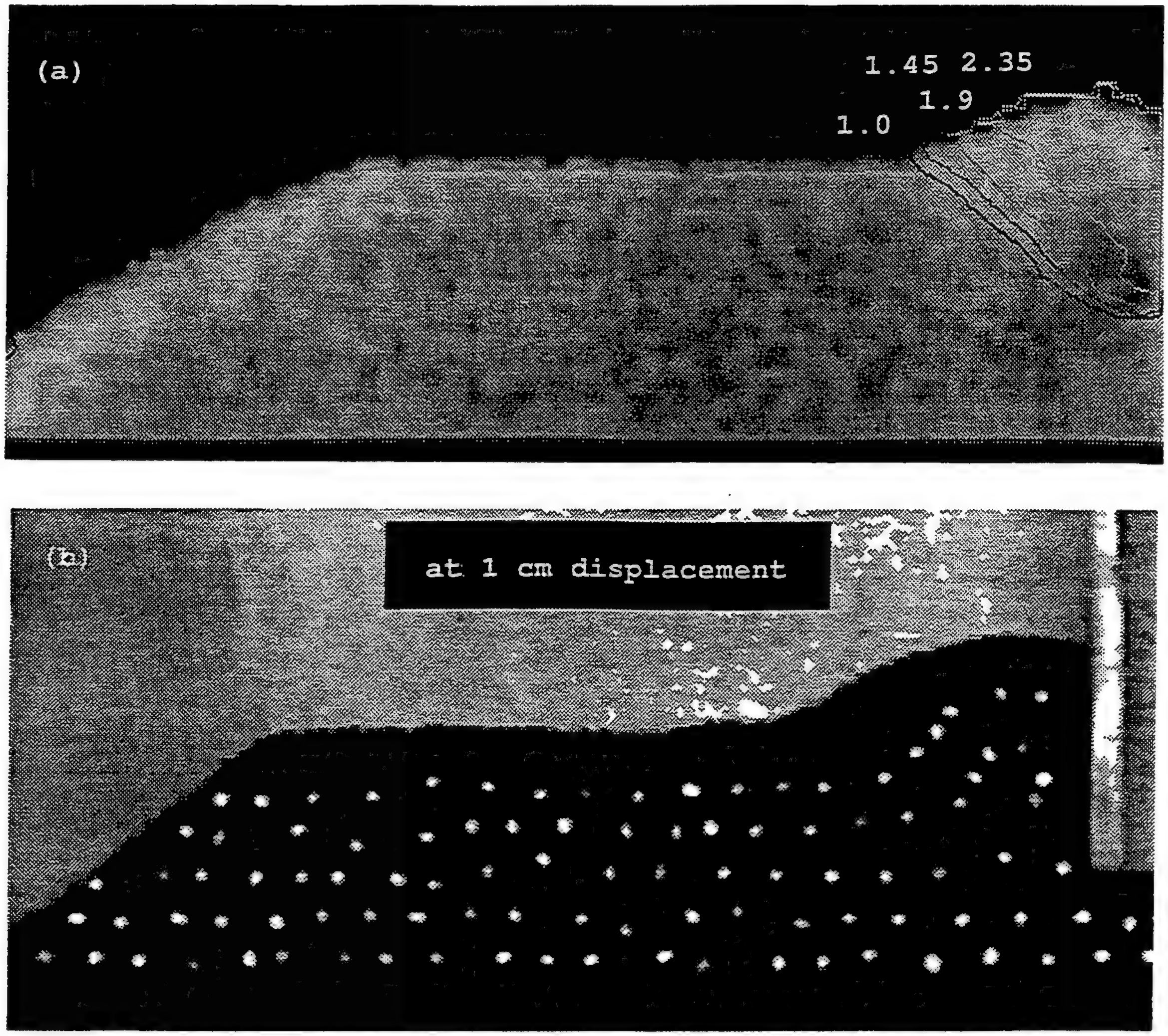
Ottawa 20-30 Sand
11.0 cm
0.85 cm
rigid base
1.0 cm
11.0 cm
1.0 cm
11.0 cm




2.54 cm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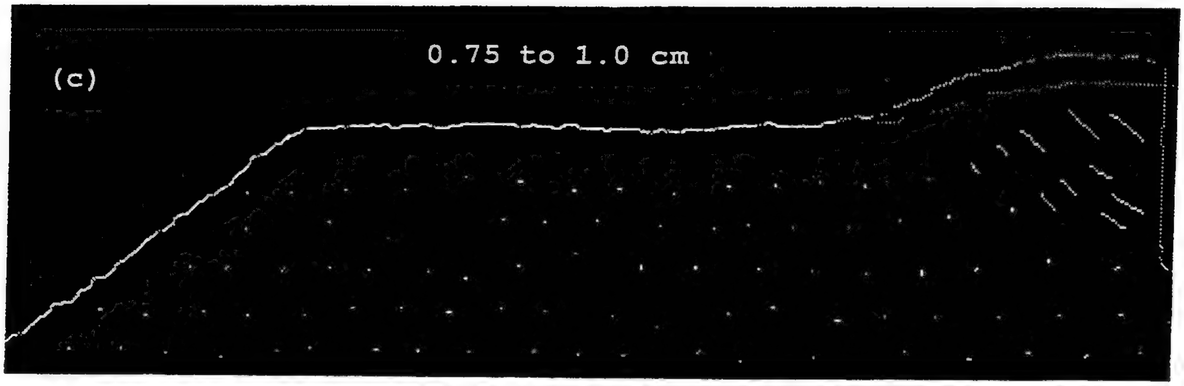
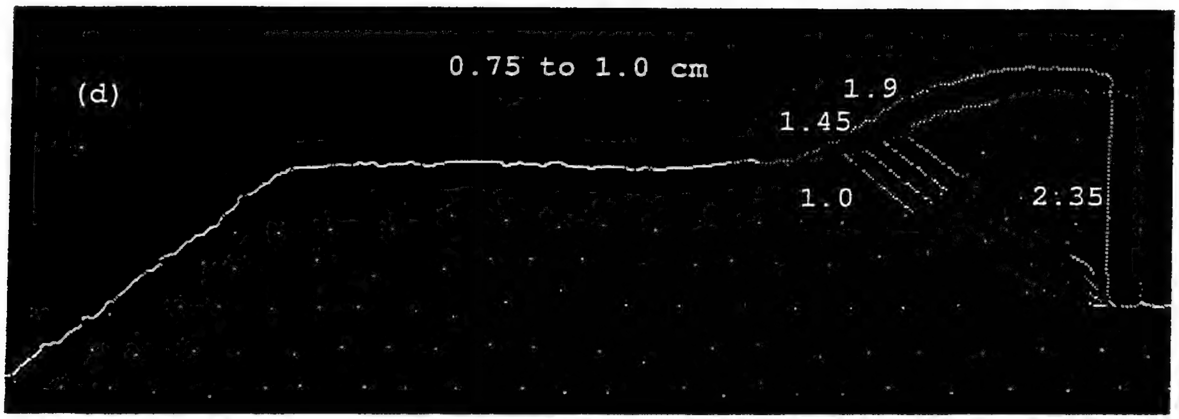
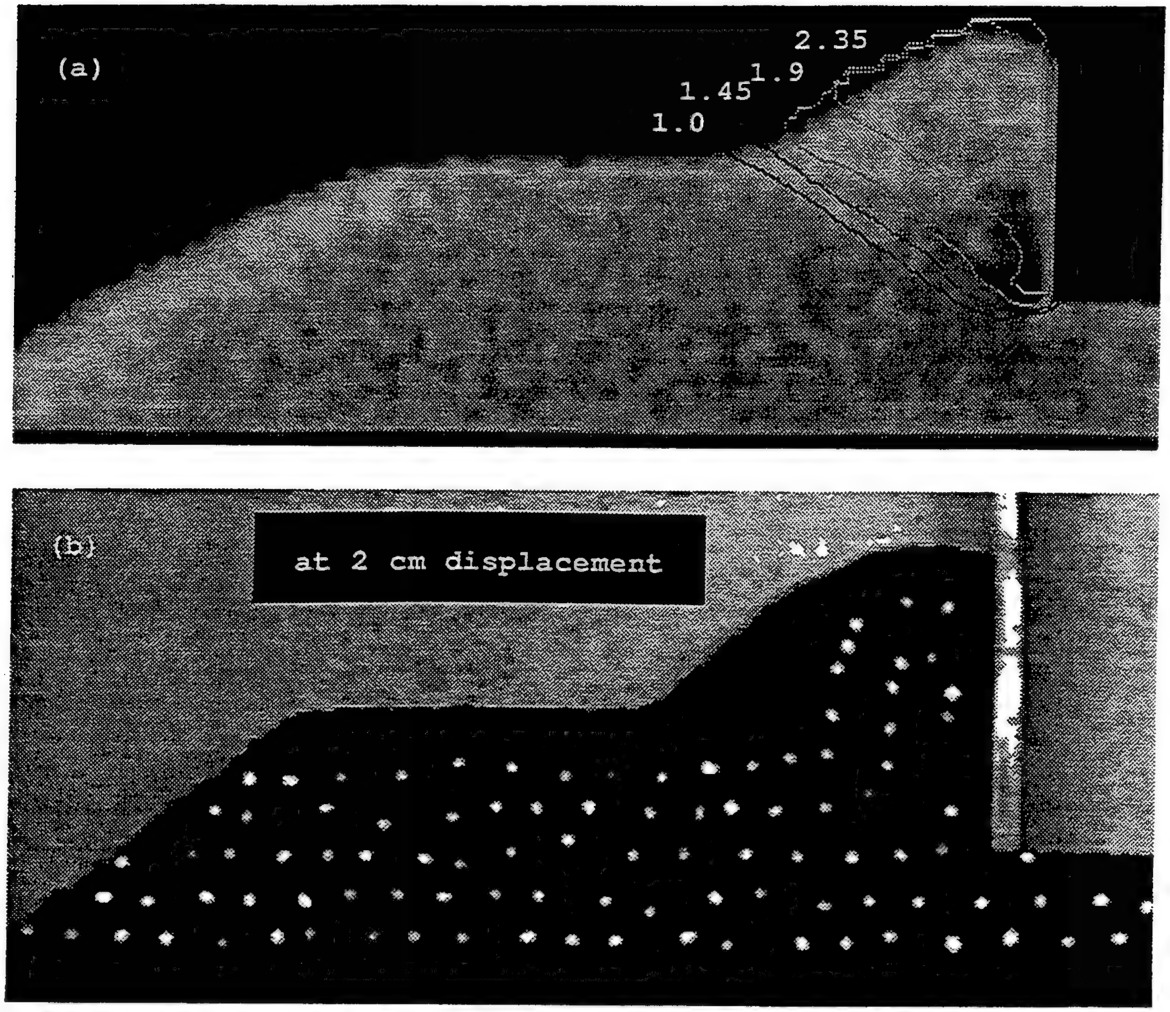
1.45 2.35
1.9
1.0
(b)
at 1 cm displacement


0.75 to 1.0 cm
(c)


0.75 to 1.0 cm
(d)
1.9
1.45
1.0
2:35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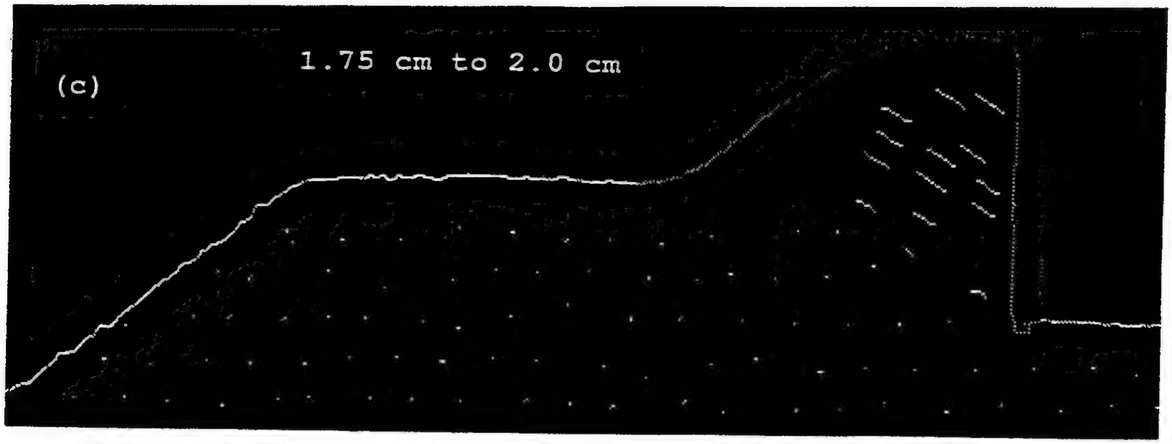
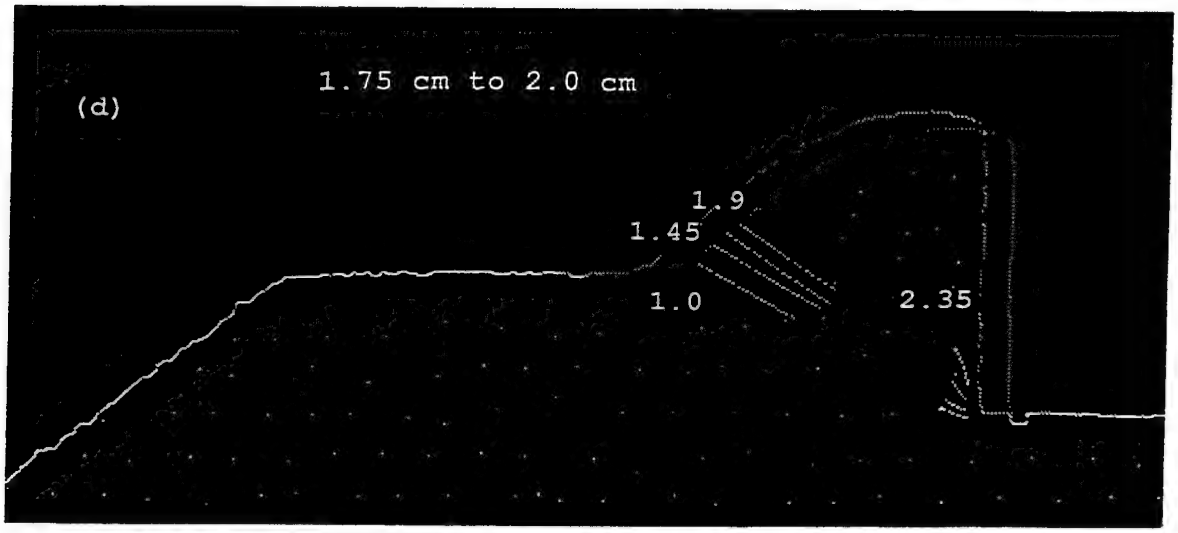
2.35
1.9
1.45
1.0
(b)
at 2 cm displacement


1.75 cm to 2.0 cm
(c)


1.75 cm to 2.0 cm
(d)
1.9
1.45
1.0
2.35

APPLIED RESEARCH ASSOCIATES, INC.

Engineering and Applied Science

A Multi-Pass Sinkage Model for Layered Soils

Prepared for:

Second North American Workshop on Modeling the Mechanics of Off-Road Mobility

March 13-15, 1996
at
U.S. Army Waterways Experiment Station
Vicksburg, MS

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March 1996

I. Introduction

Background

The Mobility Systems Division, US Army Engineer Waterways Experiment Station, is developing a robust mobility model to simulate the interaction of military vehicles with soils of various strengths. A proof-of-principle effort demonstrated the feasibility of linking a vehicle dynamics model with a soil deformation model; this was called Vehicle-Media Interaction (VMI). In lieu of basing the deformable soil model on soil properties which would require lab testing, the model was developed using the CI and RI which are readily obtainable to the field engineer. WES recognized a need for a soil model that can approximate responses observed in vehicle tests, and that can use Cone Index (CI) and Remold Index (RI) as its input parameters for soil strength.

This work follows several recommendations of our work completed in 1993 which developed a deformable soil model (VMI) and linked it to the WES/VEHDYN, a vehicle dynamics model. In 1994 we developed a detailed sinkage model for tire vehicles and implemented a scheme to use layered soil properties represented by CI and RI [3]. In 1995 the model was extended to tracked vehicles. The current tire loading model is based on work published by Dean Freitag [4]. The current track loading model is based on work published by Jackson and Hadala et al,[1 and 2]. The following summarizes the model development. The VMI has the following attributes:

1. The soil model uses CI and RI as its primary soil strength parameters. A given soil unit can strengthen or weaken, according to RI, under repeated loading. Appropriate damping parameters according to USCS soil type, CI, and RI have been determined.

2. Progressive rut depth is allowed for multiple vehicle passes. This necessitates accumulation of not only deformation, but also changing and storing soil strength (according to RI) for each terrain unit after each vehicle pass and other parameters that serve as the memory of the model.

3. A motion resistance model and a traction model have been implemented. The resistance model is a consequence of the overall VMI model implementation which uses a force follower algorithm for the vehicle loading.

This report addresses the research of the development of a wheel and track model for sinkage and presents some preliminary comparisons of the resulting model's rut depth predictions with field test results. In this report we also summarize the model development and the improvements to the overall scheme of the implementations. The motion resistance model (which is a consequence of the numerical implementation) and a traction model is also presented.

Objectives and Scope

The general objective of this research was to develop a VMI model for wheeled and tracked vehicles. The following tasks were performed:

1. Develop and implement a wheel and tracked vehicle sinkage model based on the field determined soil parameters, CI and RI. Apply the same basic approach to repeated loading and the soil damping.

2. Develop a predictive tractive capacity model of the soil to be applied at the VMI interface.

3. Review the empirical relations, especially for tires, with regard to modern tire technology, i.e., contact pressure distribution.

II. Theoretical Development

Our VMI model for tire and track (see presentation Slide 3 in Appendix) is based on the analogy of a dynamically loaded footing. As in any simulation model the determination of the parameters of the various elements lies at the heart of the predictive tool and ultimately the very usefulness of such tools. Being driven by the needs and constraints of a military environment we have here addressed several troublesome issues in the fidelity of the soil strength model. The first issue is that the strength parameters must be ones that are readily measurable in the field and can be used for field validation purposes. The second issue is related: the strength parameters must be variable with soil depth. Soils found in the field can have highly variable properties with depth; sometimes a soft top layer rests on a firm layer several inches below. The third issue which we confront is that the soil characteristics change as they are loaded, either hardening or softening under repeated loads. These three issues have made the use of classical soil strength measures problematic because of the expense involved in their field collection and laboratory analysis.

In order to develop a reasonable model which can take into account depth and repeated loading while being verifiable in the field, we have relied on the CI and RI as our primary measures, with soil density as another parameter. We used them for several reasons. First, there is an abundance of measured field data for CI and RI. Second, these are robust measures. CI is a direct measurement of force versus displacement, giving us important data on a soil's strength profile with depth that can be readily translated into a material property strength curve for use in our model. Third, the RI allows us to account for the change in soil strength with the passage of traffic, thereby making the soil either stronger (when RI > 1) or softer (when RI < 1).

The footing analogy served as the foundation for the resistance function development. This is not a new approach but it is the first time that the approach has been used for a dynamic modeling algorithm and compared with field test data. To use the footing analogy an equivalent plate bearing resistance function is needed. The basic idea was proposed by Bekker [5] in 1958.

Bekker used plates to determine the basic parameters for his function to predict load versus sinkage. His predictor was also applied to a static load and the literature seems to indicate that more detailed soil constitutive parameters were needed to improve his model. More detail is exactly the wrong way for a model to progress if it is to be used in a military application. This load displacement function predicts the compression and shearing responses of a soil deforming from a finite loaded area such as a tire or track. Three sources of very carefully controlled footing punching and tire rutting data were found in the literature [1, 2, and 4]. An exponential function ($Y = A X^{B}$) that fits the footing punching data was suggested in Reference 2. It was the similarity of this functional form and that proposed by Bekker that led us to continue the footing analogy approach. With the footing analogy approach we have a host of engineering data and methods to draw on in describing the VMI. For example, the footing is an obvious analogy to the steel tracks that we see on bulldozers, while a flexible footing approach is a reasonable approach for the tire. The dynamics of footing interaction has also been studied and is taught in earthquake and weapons engineering courses.

To verify the basic physics of the soil motion (i.e., the degree of compaction and the zones of soil mobility underneath the footing) we performed a few first principal calculations which were numerical simulations of the test performed in References 1 and 2. These calculations were performed with the dynamic finite element code HONDO [6]. This code has been extensively modified by its many users and we are no exception. We have developed a multiphase soil model that permits computations of soil deformations in soil systems that are partially saturated. The air, water and soil matrix system is represented by a Terzaghi effective stress model which is reported in detail in Reference 7.

We simulated test 17-2 of Reference 2 to with an axisymmetric calculation. The soil data, strength parameters, density, degree of saturation, etc., was obtained from the soil test also reported in Reference 2. The time history of the footing displacement (Slide 13) is in very good agreement with the test data. To inspect the zones of soil motion, the deformed grid is shown (Slide 14). Note that the grid has a zone of soil that is being sheared underneath the footing as well as at the side of the footing. The latter zone is the zone that we expect from the finite load of the footing. Note also that the shear zone underneath the footing is taking place at some distance from the footing. To exemplify further the principal shearing strains are presented (Slide 15) and the shear zones are quite evident. The extent of these zones beneath the footing are on the order of the width of the footing and this is the characteristic dimension that will be used to calculate the mobilized mass of soil that is used in the dynamic VMI calculations. Note also that the soil is moving out from under the footing in a flow like manner (Slide 16). It is this soil flow that led us to include a resistance term in our model based on flow mechanics. From these first principal calculations we have gained some insight into the dynamic soil mechanics that make up the resisting forces that are exerted on the tires and tracks.

The basic governing deferential equations are presented below. The coordinate, y, is always normal to the element or line connecting any two mass points and the x coordinate is in the line

of the connection. By using this coordinate system i.e. a local system, we can describe a realistic terrain in a global coordinate system and operate our soil resistance functions in a local system.

The governing equations are with Z representing the matrix of x and y

$$M\ddot{Z} + C\dot{Z} + KZ = F(t)$$

where
M= the soil mass
C = the Newtonian and flow damping
K = the soil load deformation functions
F(t) = the tire or track loading function

The basic numerical model is a multi-degree of freedom (two dimensional) mass, spring, and damper system. The time integration scheme is a modified central finite difference based on incremental deformations to minimize numerical error in accumulating small displacements. The form of the finite difference equations are written for the damped system of differential equations. As discussed above the local coordinate system is chosen to be normal to the terrain element for local calculations and then transformed to a global coordinate system for the dynamic integration. The origin is set by the user but is usually chosen to be on the left with the vehicle moving to the right. This is the convention used in the comparisons in this report.

This section will describe the procedures and the assumptions used in determining the parameters of the proposed VMI model for both the tire and track. Although the tire model has been reported in Reference 3 it is included here for completeness of the presentations and also there have been numerous improvements added since Reference 3.

Detailed tire sinkage data was acquired by Freitag [4]. The data were such that a simple function could be fit to model the displacement as function of non-dimensionalized soil parameters. The function fit to the data is

$$Y = A X^{B}$$

where
Y= W/C(bL) for clayey soils
Y = $W/G(bL)^{3/2}$ for sandy soils
X = z/b normalized displacement
A, B = fitting constants

This concludes the development of the single pass rut model for the tire.

The track model was developed in like manner using the dynamic footing data of References 1 and 2. The footing data was reduced using the footing width for b and hence the normalized displacement, z/b. Since References 1 and 2 did not perform cone penetration test on their soil

test beds it was necessary to estimate the Cone Index from the reported shear strength, τ, using the empirical relation

$$CI = 11.\tau .$$

Using this relation the data of footing normalized load versus displacement was obtained. Dynamics of the footing test loadings was removed from the obtained static load displacement relationship by using the simple amplification factors reported in Reference 2. This data was then fit with the same function used for the tire data and a new set of coefficients were obtained

III. Comparison With Experimental Data

Several examples have been selected to demonstrate the VMI and its implementation. This has been accomplished by computing the rut depth for several different vehicles over different soil courses. The computations were performed for multiple passes at slow speeds (0.8-1.6 km or 0.5-1.0 mph) and compared with the reported data.

Measured Versus Computed Tire Rut for Clay Soil Systems

M923 5-Ton 6X6 Cargo Truck

This mobility assessment of the M923 vehicle is reported in Reference 9 and only data pertinent to the comparisons of experimental and computed rut depth are contained in this report. Two different tire designs (Michelin and Goodyear) and four different tire pressures, 8.0, 18.0, 25.0 and 30.0 psi, were used for the 3-axle, 6 tire vehicle rutting calculations. The CI and RI data for 49 different tests were used in this preliminary model evaluation. All tests were performed at clay sites with variable density and moisture content. Each calculation was performed for the reported number of passes completed and this calculated rut depth was compared with the measured rut depth. The test results versus predicted rut depth are presented in Slide 10.

Measured Versus Computed Track Rut Depth for Clay

D7 Bulldozer

The vehicle details are reported in Reference 13. The load on the track is transferred through five 10 inch track rollers spaced 13 inches on center. Predictions versus measured data are depicted on Slide 11. In this case we were able to use measured cone index profiles for each station instead of an averaged profile. The resulting predictions fell within the scatter of the measured data.

Measured Versus Computed Wheel Rut Depth for Sand

HMMWV in Sand

Rut predictions for a sand soil system were performed for two HMMWV configurations, the M998 Utility Truck (loaded) and M1025 Armament Carrier (unloaded). The mobility assessment is reported in Reference 11. The authors provided field notes in which measured rut depths were recorded. The CI and RI for the dune sand test site were used in the predictions. There was considerable scatter in the measured rut data due primarily to the sand sloughing and the very shallow ruts.

The comparisons of the predicted with the measured ruts for the two cases selected are presented in tabular form due to the limited number of comparisons. It is not clear at this time why the apparently softer site has less measured rut depth than the stiffer site which supported a much heavier vehicle.

Comparison of Calculated and Measured Rut Depths in Sand

Vehicle	Rut Depth mm(in)	
	Predicted	Measured
Utility Truck (loaded)	50(2.04)	127-73(5.2 - 2.96)
Armament Carrier (empty)	74(3.0)	38-39(1.58 - 1.6)

IV. Conclusions

Variance between predictions and field measurements may be due to absence of a robust tire model. Variance may also be due to not applying (in this case) dynamic vehicle forces. In the current implementation there is no feed back to the loading function from the response of the VMI. Nor does the input force have a coupled inertial force that would simulate the dynamics of the vehicle. Recall that the basic premise of the model is that of a rigid/flexible footing that is punching into the soil. The current model does not attempt to simulate the transport of soil (hence effecting the rut depth) caused by the modern aggressive tire treads.

The tire-soil model provides a reasonable representation of a layered soil structure and predicts ruts according to the layered soil properties. The model is sensitive at the right places; i.e., if the RCI reflects a hardening condition with depth, the rut stops growing with increase in number of

passes. More comparisons with rut data from sand sites are needed to build confidence in the sand model approach.

V. Recommendations

The following are preliminary recommendations drawn from testing the current VMI.

1. There is a need for a good tire model. This tire model should reflect the effect of the tread design, the flexibility of the contact area, and the side wall design.

2. Commensurate with the tire model, there will be a need to modify the soil model to accommodate different tire widths. Particularly tires that are wider than the length of their foot print.

3. With the introduction of a good tire model there will be a need to investigate the effects of non-uniform pressure distributions imparted by tires and determine whether accounting for those pressures in the soil model is warranted.

4. Enhancements are advisable in the transition of the RCI values between layers in the soil model. Currently the VMI model exhibits no elastic rebound nor is there any overburden stress confinement effects.

5. A soil transport model is needed to accurately predict the rutting effects of aggressive tread designed on modern tires. This mechanism becomes more important as the rut depth increases.

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APPENDIX: Briefing Slides

A Multi-Pass Sinkage Model For Layered Soils

Prepared For:

Second North American Workshop on Modeling the Mechanics of Off-Road Mobility

March 13-15, 1996

US Army Waterways Experiment Station

Vicksburg, MS

Prepared By:

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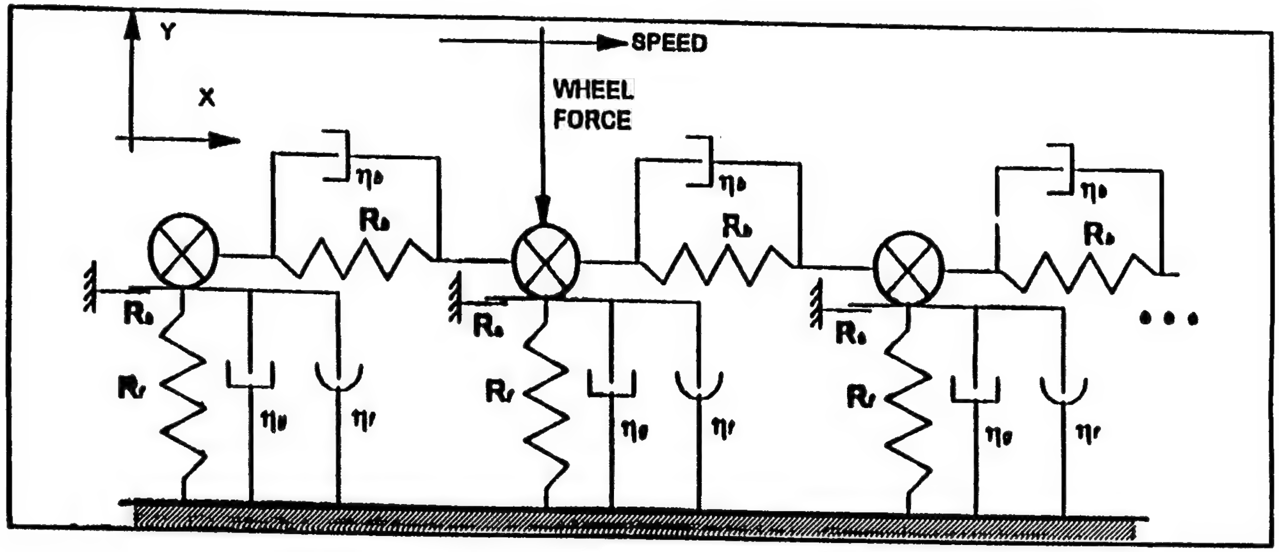
OBJECTIVES

- Develop a Vehicle-Media Interaction (VMI) model for track and tire vehicles using field-measurable soil parameters.
- Enable VMI to be coupled with a vehicle dynamics model.



R_b = Motion resistance function
R_f = Soil rutting function
R_e = Soil traction function
η_g = Radiation damper
η_f = Flow damper
η_b = Internal damper

Schematic of VMI Model

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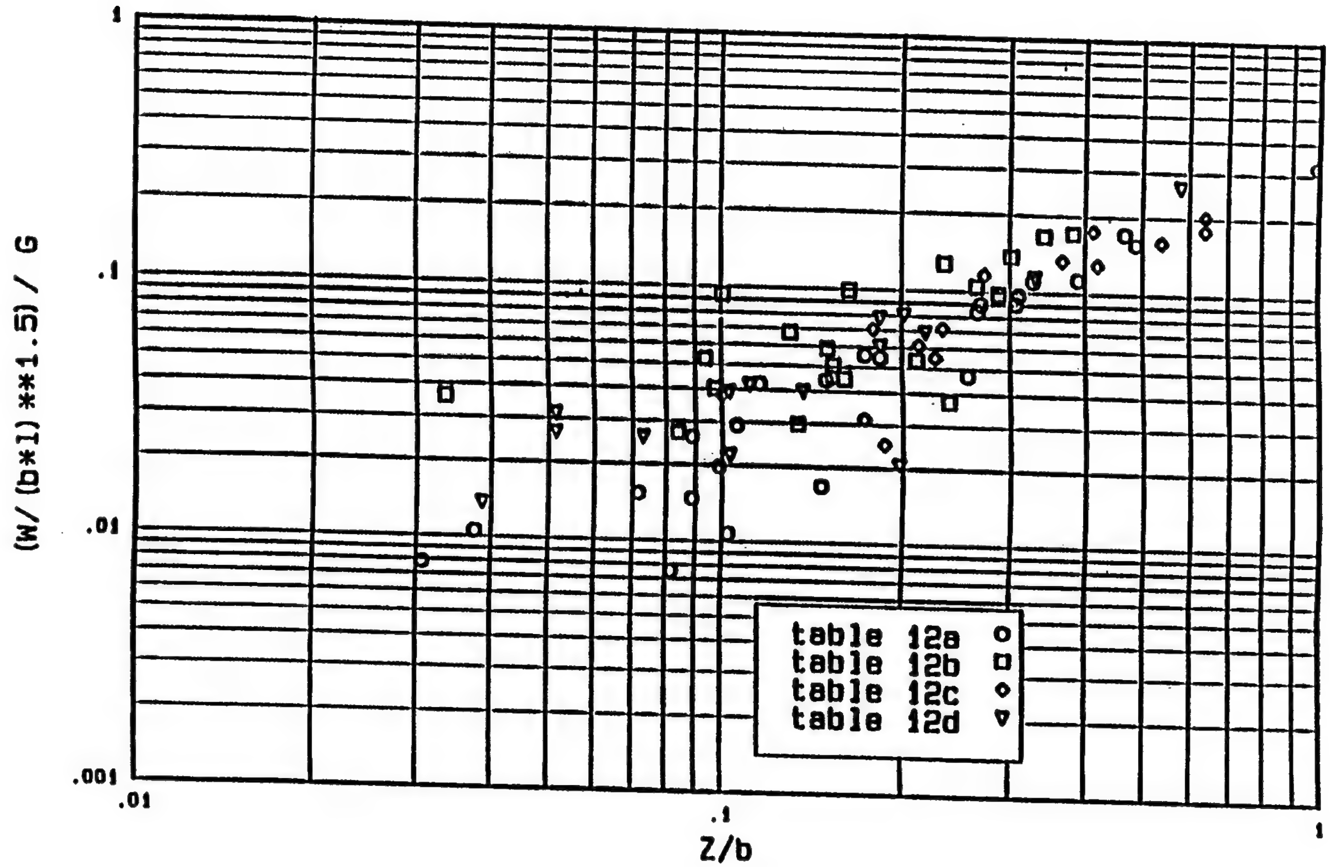

Normalized Functional Relation for Soil Resistance All Tires, Sand Tests

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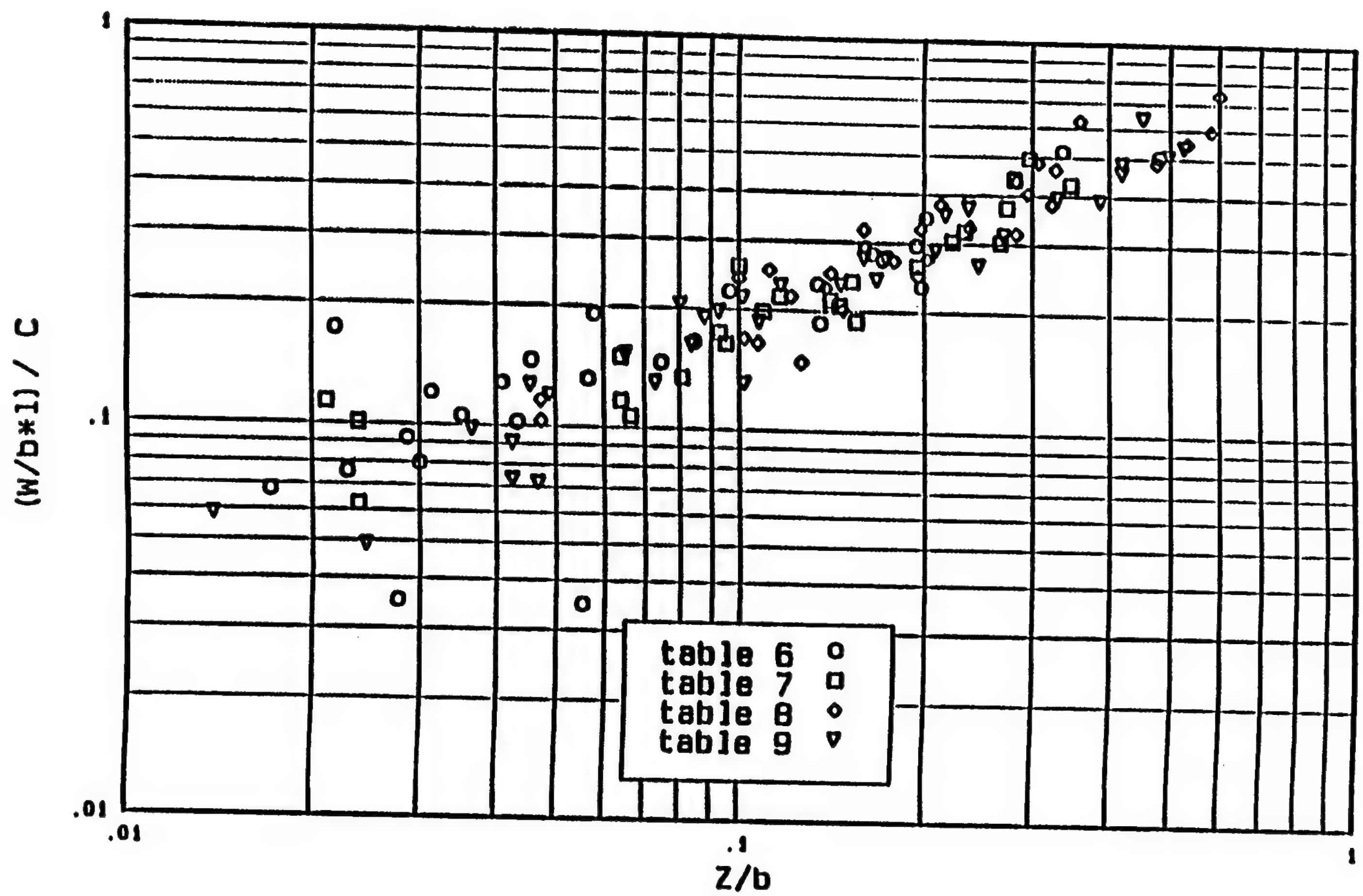
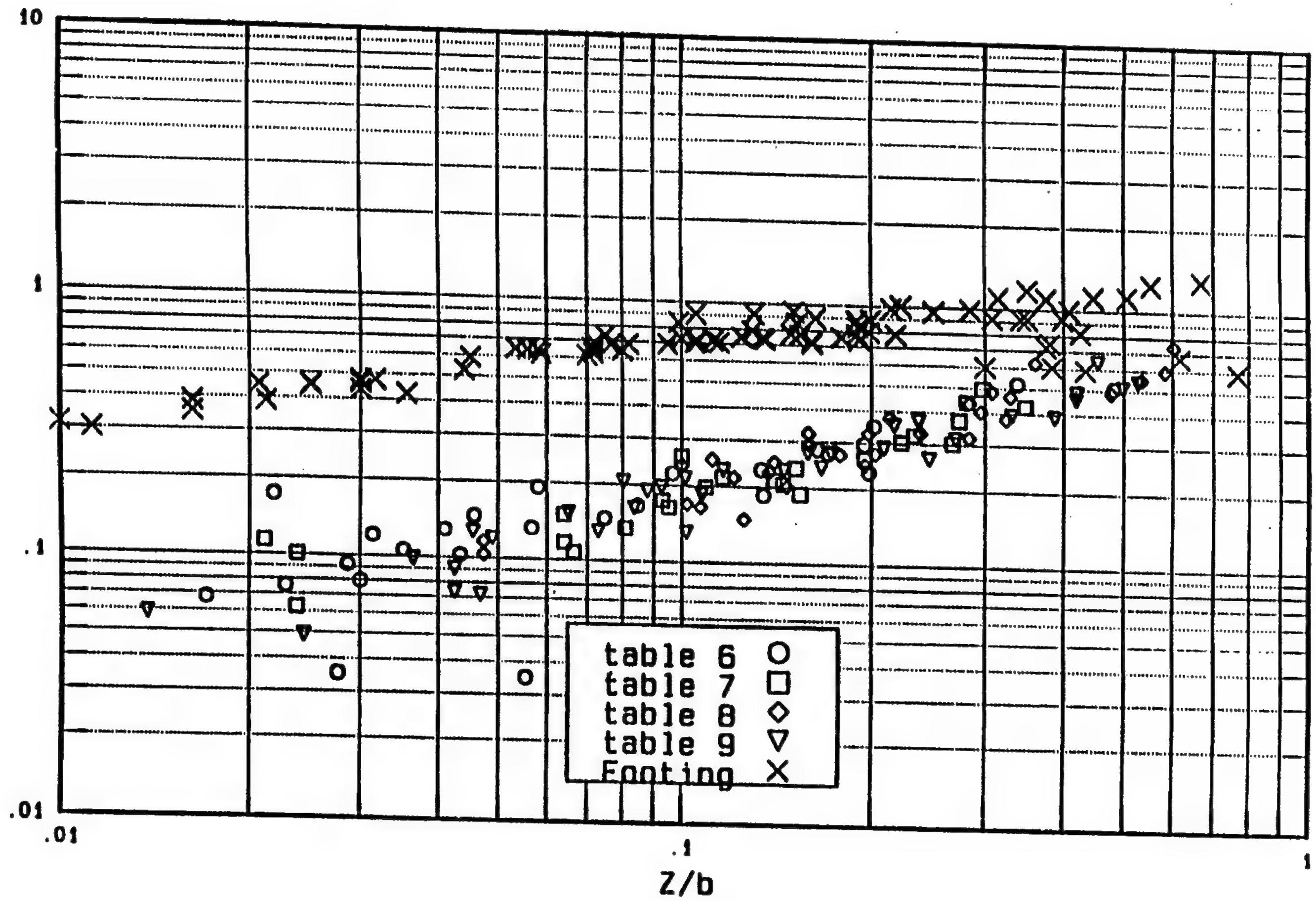


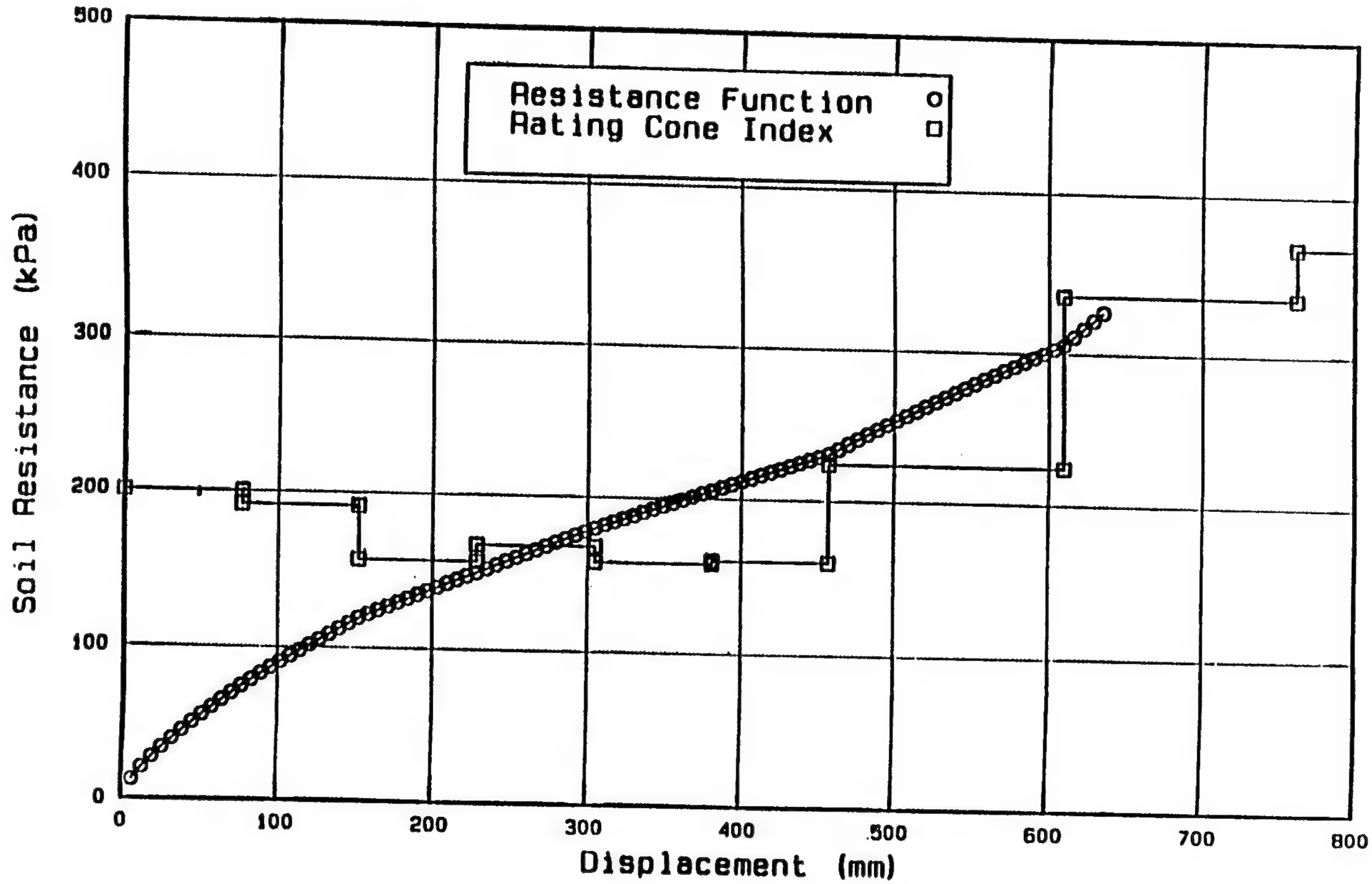
Normalized Functional Relationship for Soil Resistance All Tires, Clay

APPLIED RESEARCH ASSOCIATES, INC.



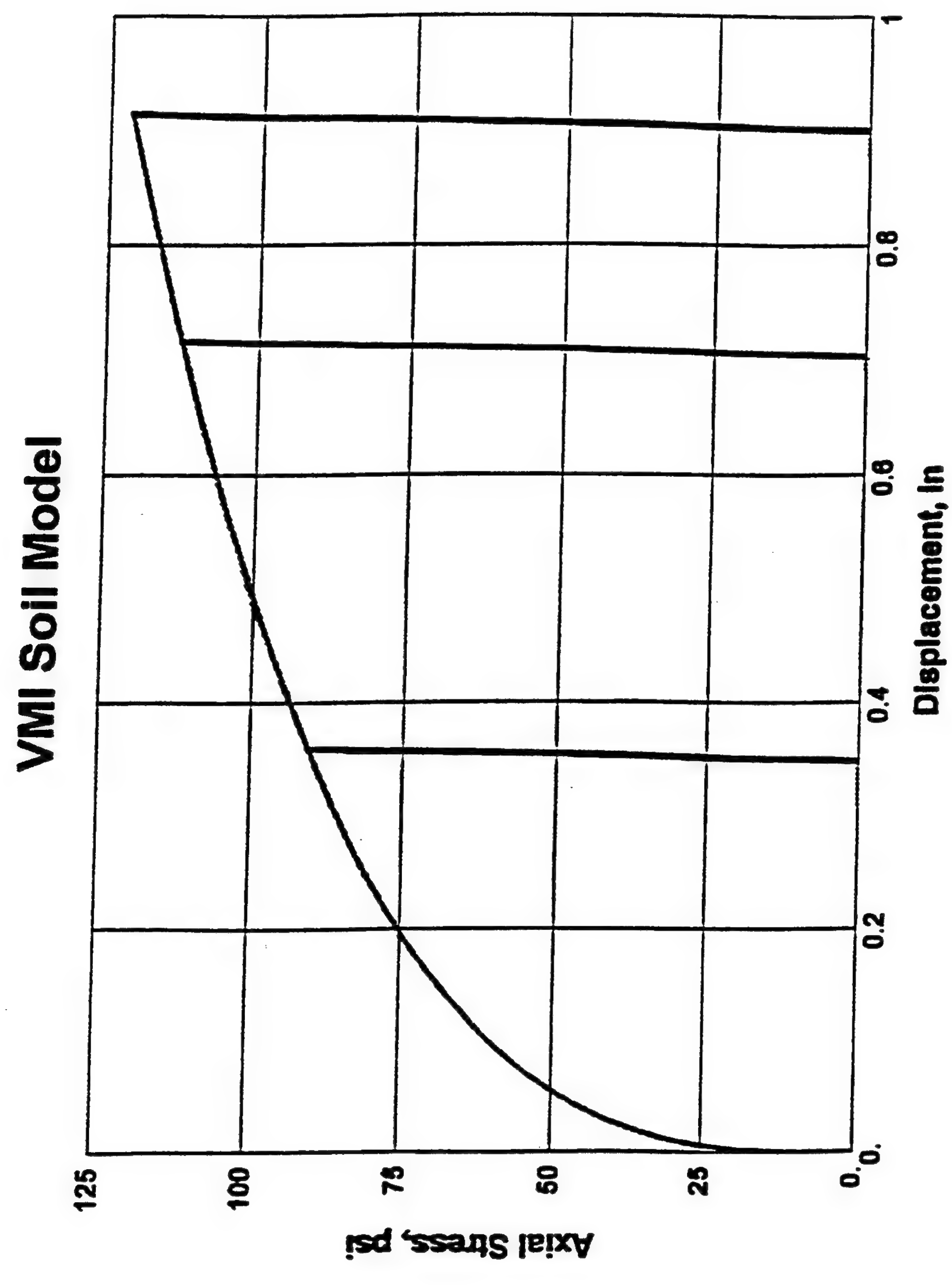
Normalized Functional Relationship for
Soil Resistance All tires and footings-Clay

APPLIED RESEARCH ASSOCIATES INC.



Typical Load Displacement Function Used by VMI for a Clay Site (TLAR Test 9)

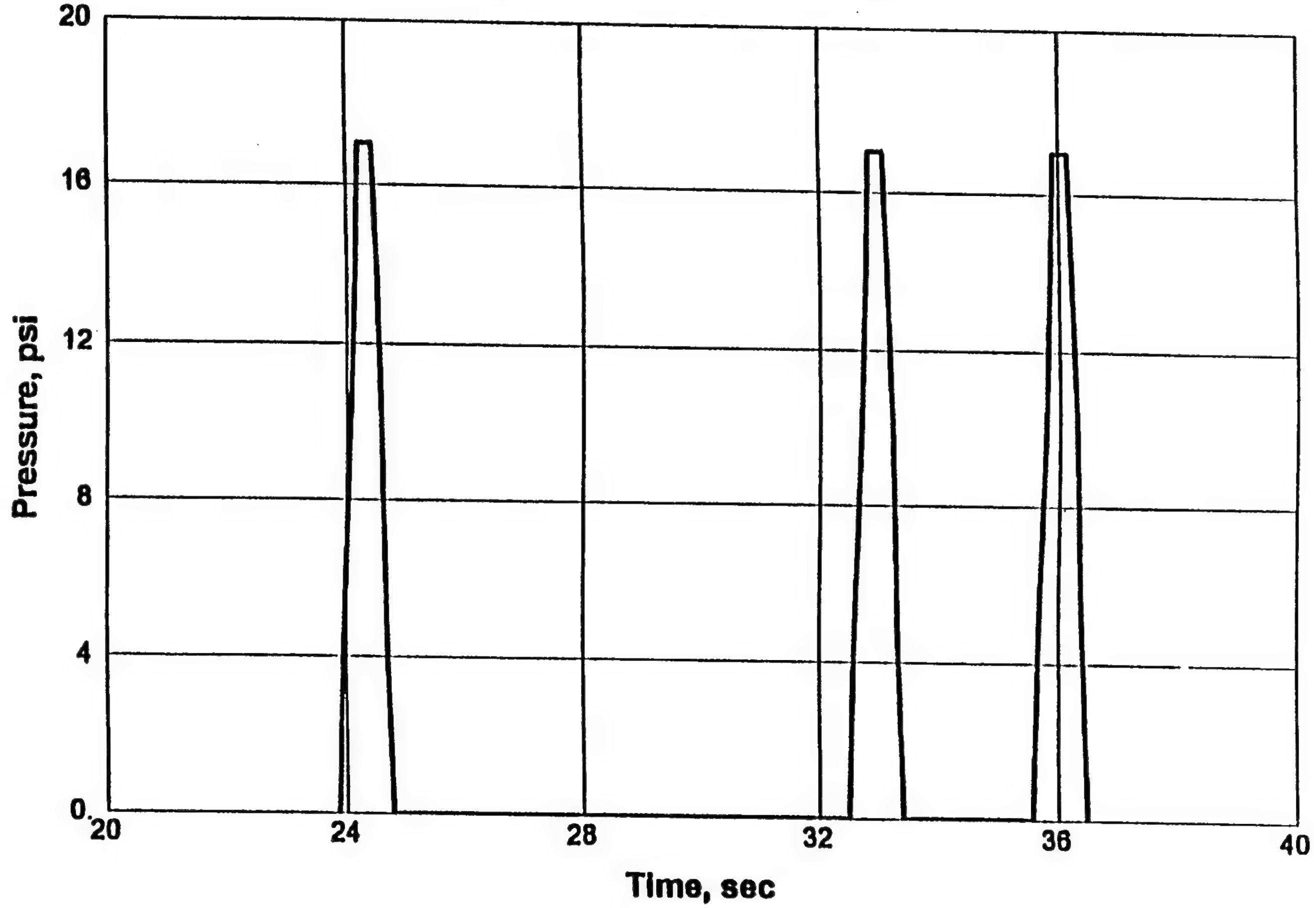
APPLIED RESEARCH ASSOCIATES, INC.



APPLIED RESEARCH ASSOCIATES, INC.

M923 5 Ton Cargo Truck

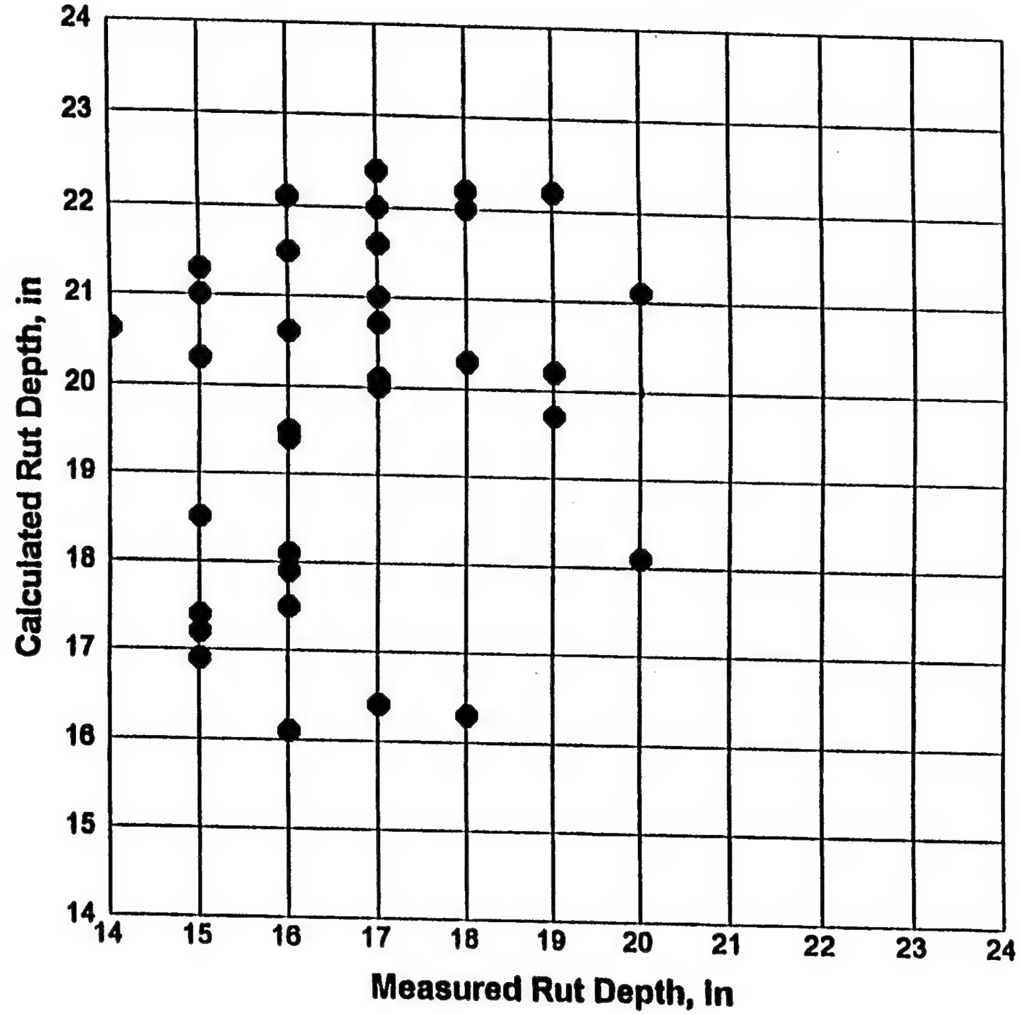
Vehicle Load Time History



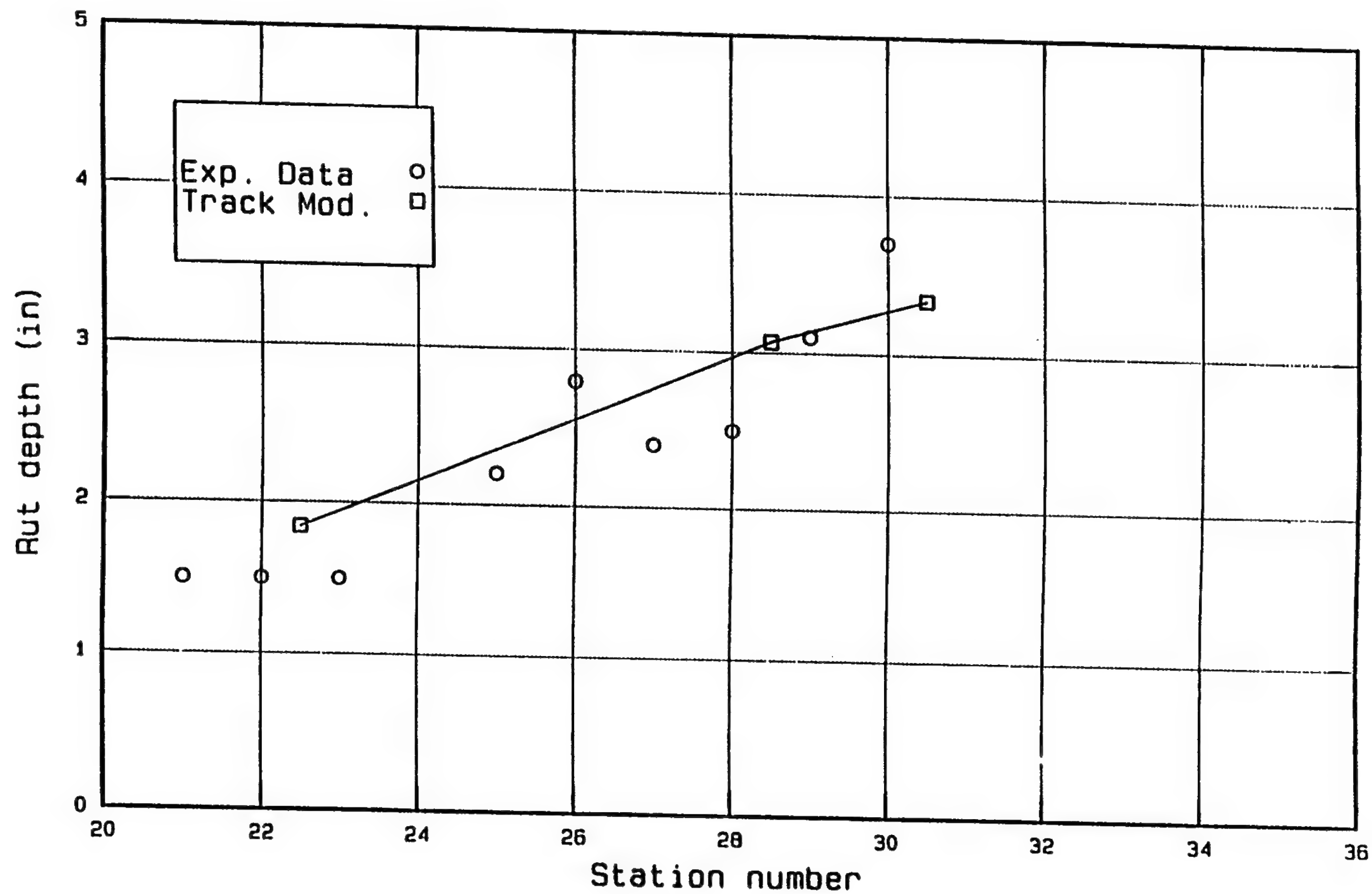
APPLIED RESEARCH ASSOCIATES, INC.

M923 5-Ton Cargo Truck

calculated rut depth versus measured



APPLIED RESEARCH ASSOCIATES, INC.



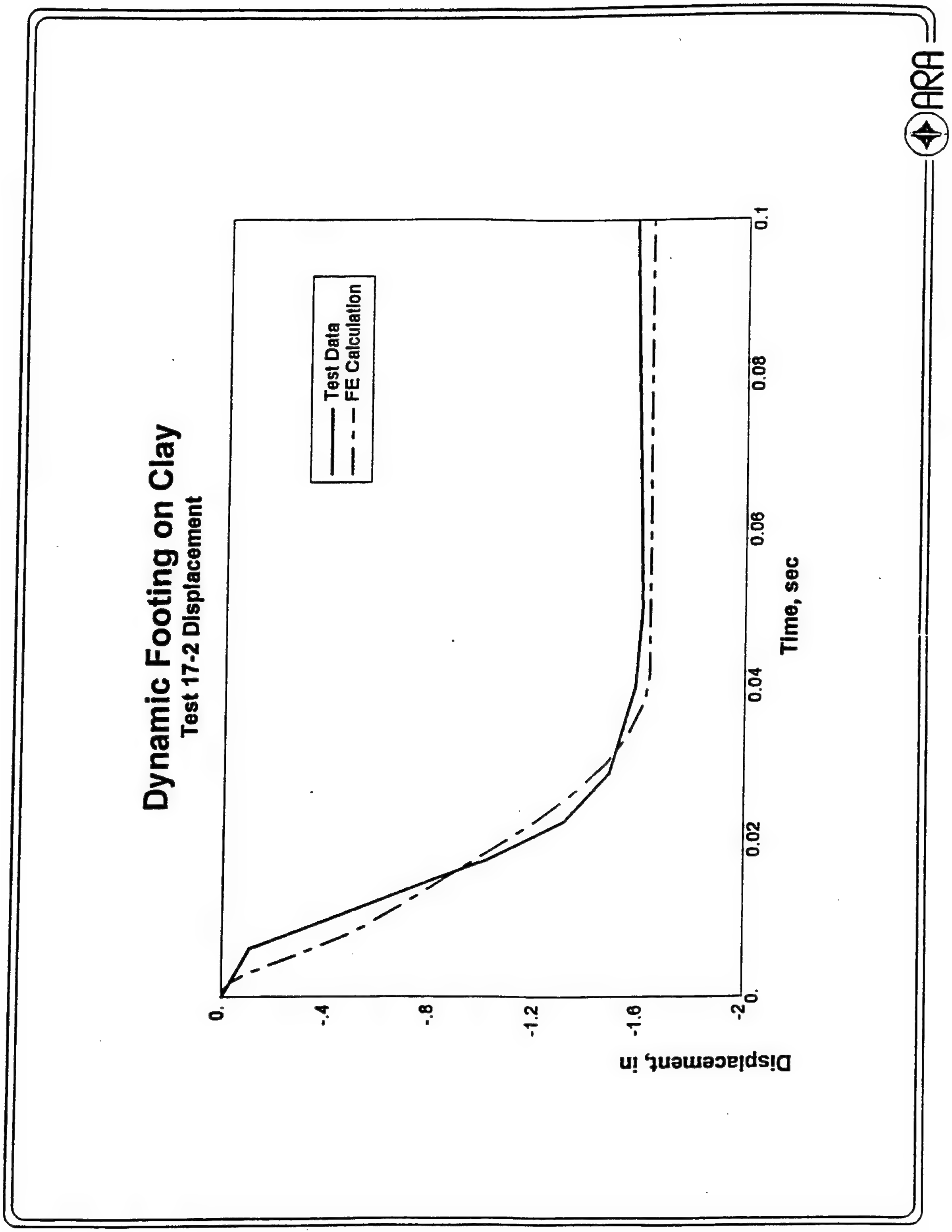
Rut vs Station No.after 5 passes, D7 Tractor
Using Track Model for VMI

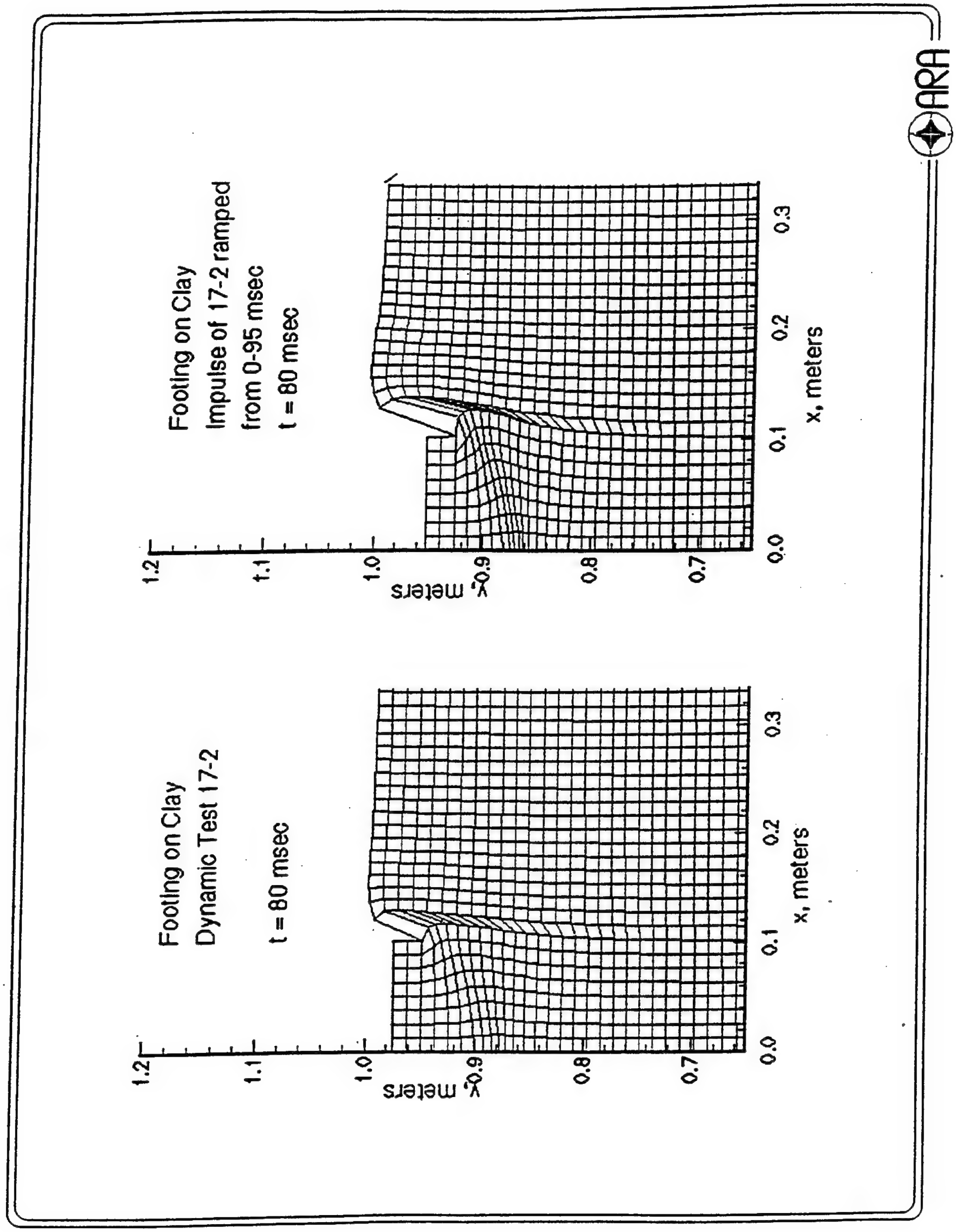
APPLIED RESEARCH ASSOCIATES, INC.

Conclusions / Recommendations

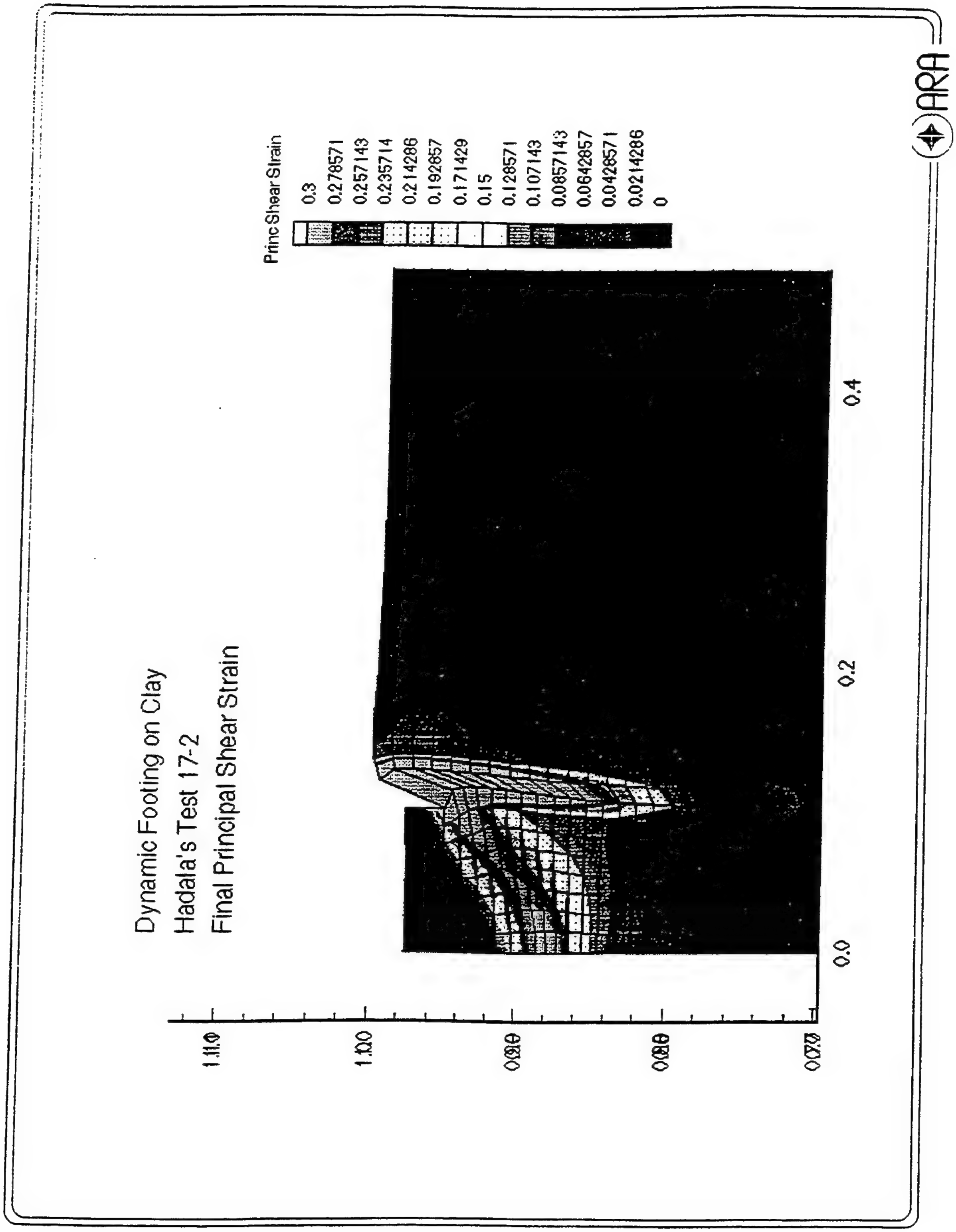
- VMI model performs as expected provides reasonable responses..
- On the average current model predicts less rutting depth than field test data.
- More detailed representation of the load-unload-reload cycle is needed.
- Influence of tread depth and design are needed to develop soil transport mechanism for the VMI.

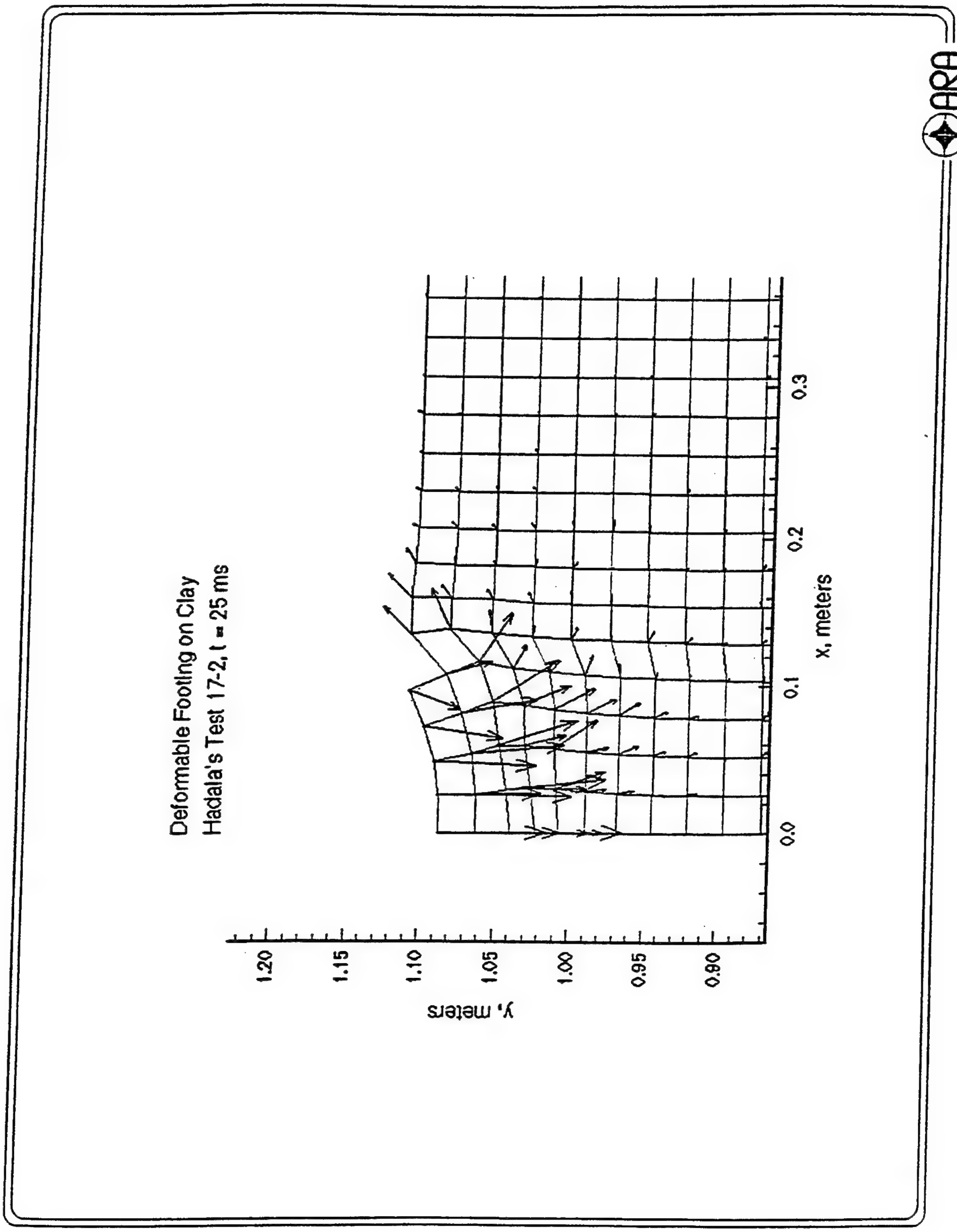
APPLIED RESEARCH ASSOCIATES, INC.


Dynamic Footing on Clay
Test 17-2 Displacement
Test Data
FE Calculation
Displacement, in
0.
-.4
-.8
-1.2
-1.6
-2
Time, sec
0.
0.02
0.04
0.06
0.08
0.1
ARA



Footing on Clay
Dynamic Test 17-2
t = 80 msec
y, meters
x, meters
1.2
1.1
1.0
0.9
0.8
0.7
0.0
0.1
0.2
0.3
Footing on Clay
Impulse of 17-2 ramped
from 0-95 msec
t = 80 msec
y, meters
x, meters
1.2
1.1
1.0
0.9
0.8
0.7
0.0
0.1
0.2
0.3
ARA


Dynamic Footing on Clay
Hadala's Test 17-2
Final Principal Shear Strain
Princ Shear Strain
0.3
0.278571
0.257143
0.235714
0.214286
0.192857
0.171429
0.15
0.128571
0.107143
0.0857143
0.0642857
0.0428571
0.0214286
0
0.0
0.2
0.4
ARA



Deformable Footing on Clay
Hadala's Test 17-2, t = 25 ms
y, meters
1.20
1.15
1.10
1.05
1.00
0.95
0.90
x, meters
0.0
0.1
0.2
0.3
ARA

A LARGE-SCALE SOIL MOISTURE MODEL

Elfatih A. B. Eltahir, Room 48-207, MIT, Cambridge MA 02139

A soil moisture model that integrates analytically a point description of the essential hydrologic processes from local to large spatial scales, and from hourly to monthly time scales is presented in this paper. Our approach emphasizes the role of spatial variability in the dynamics of water balance. The resulting scheme describes the evolution of the spatial average of soil moisture within each cell of a global model. The components of this scheme describe the hydrologic processes that govern the evolution of the soil moisture state. These processes include: surface runoff, infiltration, groundwater runoff, snow accumulation and melting, and evapotranspiration. In relatively warm conditions, the model is based on the water balance equation.

$$D\frac{\partial E(\bar{s})}{\partial t} = E(\bar{P}) - E(\bar{R}) - E(\bar{G}) - E(\bar{E}) \qquad (1)$$

where D is the average available storage depth of the soil (the porosity multiplied by the average soil depth), s is soil level of saturation which varies between zero and one, P is precipitation, R is surface runoff, G is groundwater runoff, and E is evapotranspiration. The overbar denotes averaging over large areas (~ 100 kilometers), and the $E(\ )$ denotes averaging over time (~ a month). For solid precipitation, the coupled mass and energy conservation equations that describe the dynamics of snow accumulation and melting have to be solved simultaneously.

In describing hydrologic processes over large areas, we will follow a methodology that blends physical considerations of the local hydrologic processes with statistical treatment of spatial and temporal variability. A similar approach has been followed by Entekhabi and Eagleson (1989) and Eltahir (1993). The objective is to develop simple parsimonious descriptions of these hydrologic processes that are valid at a macroscopic averaging level (hundreds of kilometers/monthly time scale). The main reason for adopting parsimonious descriptions is to insure that calibration of the model will be feasible given the typical scarcity of the data that is available with global coverage. The following section illustrates this approach using the example of surface runoff.

Surface Runoff

In formulating a simple model of runoff production, the infiltration capacity of the soil must first be described. Infiltration under homogeneous conditions is well described by Philip's (1957) and Parlange's (1971) solutions of Richard's Equation. Unfortunately, even the use of these models would represent a compromise since they cannot adequately account for observed soil heterogeneity (Gelhar, 1993) macropores (Beven and Germann, 1982), and other complicating factors.

Here we propose a simple, parsimonious infiltration model which captures only the most basic tendencies of the process. The proposed relationship includes only the influence of soil type and the level of soil saturation:

$$F = \alpha(1 - s) \tag{2}$$

Here, F is the infiltration capacity, α is infiltration capacity of dry soil, and s is the initial soil saturation level prior to occurrence of rainfall which varies from 0 to 1. Soil saturation is defined as the ratio of the volume of water to the volume of voids. This relationship implies that infiltration capacity is maximum when the top soil layer is initially dry and linearly approaches zero for initially saturated soil.

The natural heterogeneity in the distributions of precipitation and soil moisture will be treated explicitly using statistical distributions that are selected based on observations of soil moisture distributions. Precipitation supplies the water for infiltration and is allowed in this analysis to vary spatially. Given that rainfall at any time occurs only over a portion of any land region, the (conditional) distribution of the storm rainfall depth in that portion is assumed to be exponential following the observations of Eagleson et al. (1987). The distribution of precipitation over the entire region can therefore be described as:

$$f_P = (1-\mu)\delta(P) + \frac{\mu^2}{\overline{P}} e^{-\frac{\mu P}{\overline{P}}} \tag{3}$$

where P is the rainfall rate, μ is the fraction of area receiving precipitation, $\delta(P)$ is the Dirac delta function of P, and $\overline{P}$ spatial average of rainfall. Soil saturation is also allowed to vary in space but according to an Erlang distribution:

$$f_s = \frac{k^k}{\overline{s}^k (k-1)!} s^{k-1} e^{-\frac{k}{\overline{s}}s} \tag{4}$$

where $\overline{s}$ is the spatial average of soil saturation and k is a parameter that describes the shape of the statistical distribution of soil moisture.

Surface runoff production can occur either by Hortonian or Dunne runoff, so the total runoff may be described as the sum of the runoff produced by these two processes:

$$R = R_H + R_D \tag{5}$$

where R is total surface runoff, R_H is Hortonian runoff (infiltration-excess), and R_D is Dunne runoff (saturation-excess). Hortonian runoff occurs when the intensity of rainfall is greater than the infiltration capacity of the soil, and Dunne runoff occurs when precipitation falls on soil that is already saturated. Mathematically, these concepts can be described as:

$$R = \int_{s=0}^{1}\int_{P=F}^{\infty} (P - F) f_P dP f_s ds + \int_{s=1}^{\infty}\int_{P=0}^{\infty} P f_P dP f_s ds. \tag{6}$$

(note that s can not exceed 1, hence all the values of s that are greater than one are treated as if they were one and hence the corresponding mass in the probability distribution defines the saturated fraction of the area) After substituting the earlier relations for infiltration capacity and

the distribution of precipitation and performing the integration with respect to P, the equation becomes:

$$R = \frac{\overline{P}}{\overline{s}^k} \frac{k^k}{(k-1)!} e^{-\frac{\mu\alpha}{\overline{P}}} \int_{s=0}^{1} e^{C_1 s} s^{k-1} ds + \overline{P} \int_{s=1}^{\infty} f_s ds \tag{7}$$

where C_1 is defined as:

$$C_1 \equiv \frac{\mu\alpha}{\overline{P}} - \frac{k}{\overline{s}}. \tag{8}$$

These equations describe the process of surface runoff production at the hourly time scale over large areas.

A linear relationship between storm area and rainfall volume has been well documented by observations (see Eltahir and Bras (1993)) and is commonly used for the estimation of rainfall volume from radar measured storm area. Eltahir and Bras (1993) have suggested using this relation to estimate the fractional coverage of precipitation in a climate model's grid cell or a hydrologic region. Assuming a unique conditional distribution of rainfall, they have shown that the ratio of the spatial mean of precipitation to the fraction of the region receiving rain is constant and equal to the climatological rainfall intensity, i:

$$\frac{\overline{P}}{\mu} = i. \tag{9}$$

This is a critical result in the proposed model formulation since it removes the temporal distribution of precipitation from the theoretical development, replacing two variables with one constant, i. Utilizing the above relationship (Equation 10) , C_1 becomes simply:

$$C_1 = \frac{\alpha}{i} - \frac{k}{\overline{s}}. \tag{10}$$

The above integral for runoff (Equation 7) can be evaluated analytically, although its exact form will depend on the parameter k. By dividing the runoff by the mean rainfall rate, the instantaneous runoff coefficient can be determined. For $k = 1$, the runoff coefficient becomes:

$$r \equiv \frac{R}{\overline{P}} = \frac{e^{-\left(\frac{\alpha}{i}\right)}\left(e^{C_1} - 1\right)}{\overline{s} C_1} + e^{-\frac{1}{\overline{s}}}. \tag{11}$$

Unfortunately, the usefulness of this relationship is limited by a lack of soil moisture data on the time scale of rainfall events.

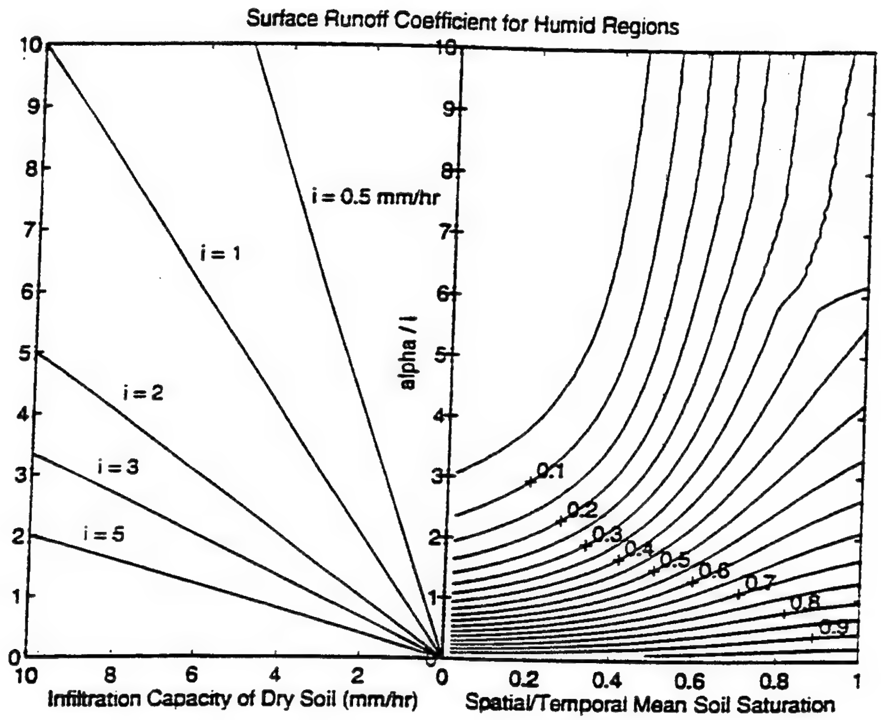
The climatological (space/time average) runoff coefficient can be derived from Equation 12 by employing an Erlang model for the temporal distribution of mean soil saturation:

$$f_{\overline{s}} = \left[\frac{1}{\int_{\overline{s}=0}^{1} \frac{\kappa^\kappa}{E(\overline{s})^\kappa (\kappa-1)!} \overline{s}^{\kappa-1} e^{-\frac{\kappa \overline{s}}{E(\overline{s})}} d\overline{s}} \right] \frac{\kappa^\kappa}{E(\overline{s})^\kappa (\kappa-1)!} \overline{s}^{\kappa-1} e^{-\frac{\kappa \overline{s}}{E(\overline{s})}} \tag{12}$$

where $E(\bar{s})$ is the spatial/temporal mean of soil saturation. Notice that the mean soil saturation cannot be greater than one, so the distribution is normalized with its integral from 0 to 1 (the factor enclosed in brackets). Climatological runoff coefficient, $E(\bar{r})$, is simply:

$$E(\bar{r}) = \int_{\bar{s}=0}^{1} \bar{r} f_{\bar{s}} \, d\bar{s} \qquad (13)$$

which can be evaluated numerically. This equation for climatological runoff coefficient depends on five variables: α, the parameter which describes the infiltration capacity of a completely dry soil; i, the climatological rainfall intensity; k and κ which are functions of soil moisture climatology; and $E(\bar{s})$, the spatial/temporal mean of soil saturation.



This Figure shows the climatological runoff coefficient as a function of mean soil saturation, $E(\bar{s})$, infiltration capacity of dry soil, α, and climatological rainfall intensity, i. The ratio of α to i can be determined using the left side of the graph. Then with a known $E(\bar{s})$, the runoff coefficient can be determined from the right hand side. The product of precipitation and the climatological runoff coefficient is surface runoff.

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JOHN DEERE PRODUCT ENGINEERING CENTER

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SUBJECT: VEHICLE SIMULATION AT THE JOHN DEERE PEC

Introduction:

The paper was written in response to the request for attendees of the Second North American Workshop on Modeling the Mechanics of Off-Road Mobility to prepare a paper describing their current work. A majority of my work is modeling future vehicles at the John Deere Product Engineering Center. Therefore my work tends to be proprietary or confidential. I will make an attempt to provide some insight to my work with out violating proprietary restrictions.

POWER HOP IN AGRICULTURAL TRACTORS

Power hop is a phenomenon which is exhibited when a tractor is subjected to large draw bar loads. Power hop is manifested in a vertical bounce motion which, in worst case situations, can build to an amplitude where the tractor tires actually leave the ground. I am participating on a team of experts who are developing a more thorough understanding of the hop phenomenon through detailed vehicle modeling and validation tests which will be used to refine the model. This model includes the affect of tires, engine power curve, drive line wind-up, and the tire ground interface.

DYNAMIC SIMULATION OF TRACK VEHICLE

A dynamic simulation model of track vehicle for agricultural use is being used to evaluate vehicle performance characteristics which include ride, steering, and dynamic structural loads. The track vehicle model has been used to predict dynamic structural loads over various smooth and rough road profiles. These loads are use in FEA models to predict the structural integrity of the track vehicle. The model has also been used evaluate and tune the cab mounts for optimum ride characteristics. The most challenging characteristic to model is the steering performance of the track vehicle. Work is continuing in this area.

DYNAMIC SIMULATION TOOLS

The dynamic vehicle models are primarily created in DADS, the multibody mechanical systems software created by CADSI in Coralville, IA. Specialized subroutines representing the vehicle hydraulics and power systems are modeled in Easy5, from Boeing, are integrated into the DADS model. The models are run on SGI Onyx computers.

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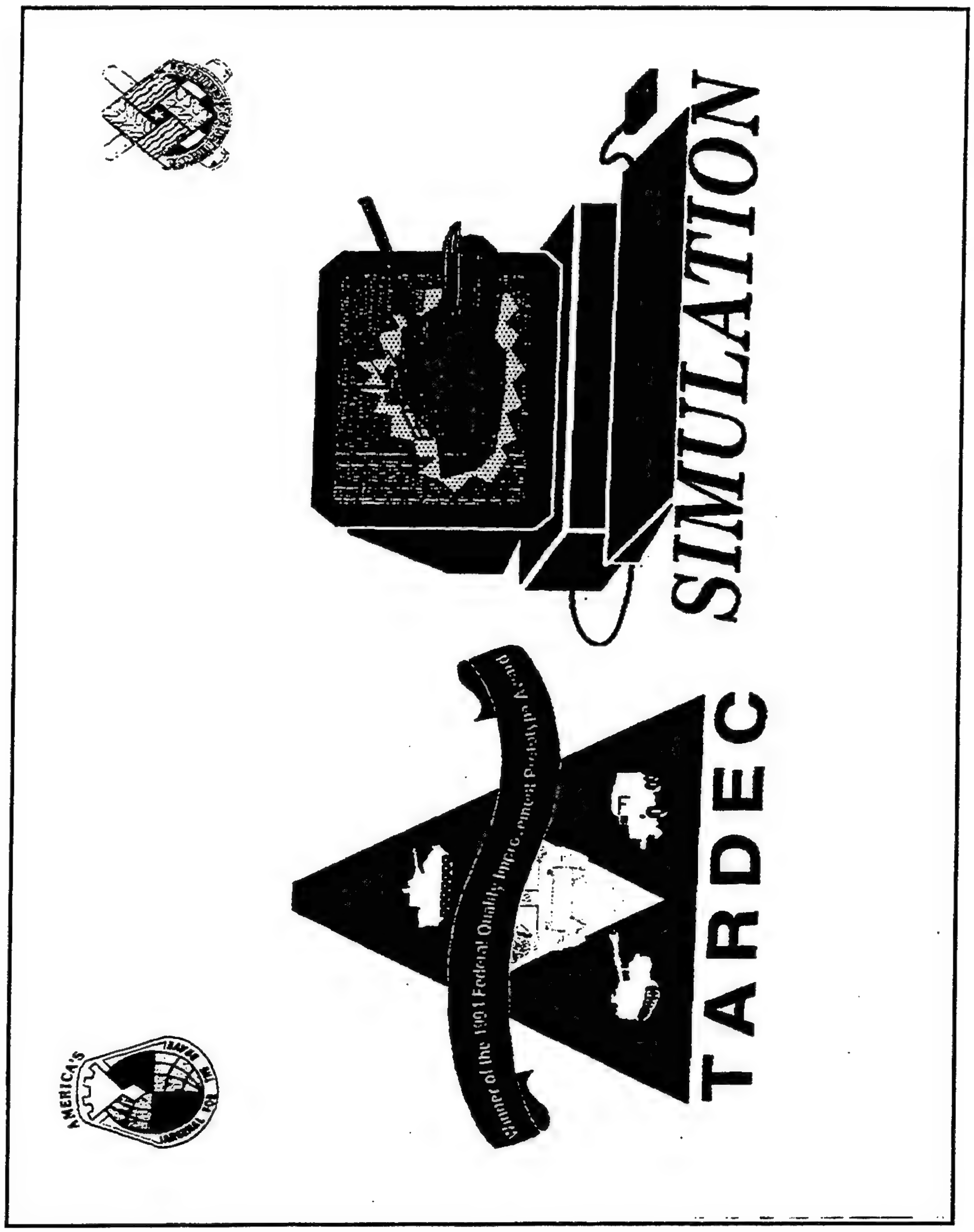
Appendix D
Presentation Slides


TARDEC
SIMULATION
Winner of the 1991 Federal Quality Improvement Prototype Award
AMERICA'S

Ground Vehicle Modeling & Simulation

Goal is to make it an integral part of the acquisition process:

- Streamline the process
- Reduce the development cycle & associated costs
- Incorporate into test & evaluation (MOP / MOE /MOO)

Advance the associated technology:

- Develop & apply state-of-the-art tools (analytical & physical)
- Incorporate it into the RDE business

Provide technology transfer opportunities:

- Share government developed tools & facilities
- Establish a common analysis base between government & industry

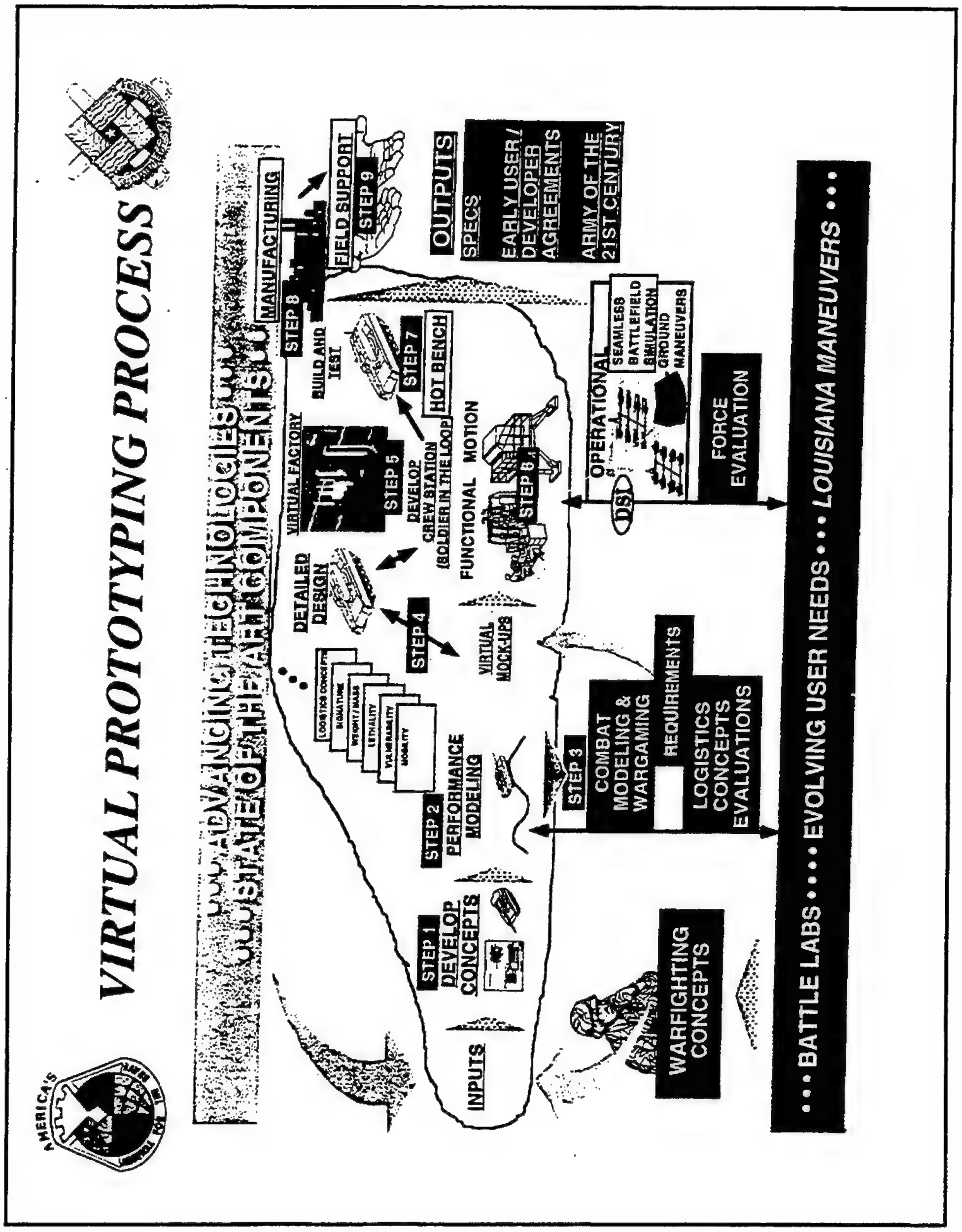
TARDEC

TANK-AUTOMOTIVE RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

TARDEC

"GENESIS OF MODELING METHODS USED"

- IN-HOUSE DEVELOPED
- COMMERCIAL PACKAGES
  - LEASED
  - PURCHASED
- JOINTLY DEVELOPED MODEL (UNIVERSITY/GOVERNMENT)
- PUBLIC DOMAIN SIMULATION TOOLS (UNIVERSITY)



VIRTUAL PROTOTYPING PROCESS
ADVANCING TECHNOLOGIES
STATE OF THE ART COMPONENTS
INPUTS
STEP 1
DEVELOP CONCEPTS
STEP 2
PERFORMANCE MODELING
LOGISTICS CONCEPTS
SIGNATURE
WEIGHT / MASS
LETHALITY
VULNERABILITY
MOBILITY
STEP 3
COMBAT MODELING & WARGAMING
REQUIREMENTS
LOGISTICS CONCEPTS EVALUATIONS
STEP 4
VIRTUAL MOCK-UPS
DETAILED DESIGN
STEP 5
DEVELOP CREW STATION (SOLDIER IN THE LOOP)
VIRTUAL FACTORY
FUNCTIONAL MOTION
STEP 6
STEP 7
HOT BENCH
BUILD AND TEST
STEP 8
MANUFACTURING
STEP 9
FIELD SUPPORT
DSI
OPERATIONAL
SEAMLESS BATTLEFIELD SIMULATION
GROUND MANEUVERS
FORCE EVALUATION
OUTPUTS
SPECS
EARLY USER / DEVELOPER AGREEMENTS
ARMY OF THE 21ST CENTURY
WARFIGHTING CONCEPTS
• • • BATTLE LABS • • • • EVOLVING USER NEEDS • • • LOUISIANA MANEUVERS • • •

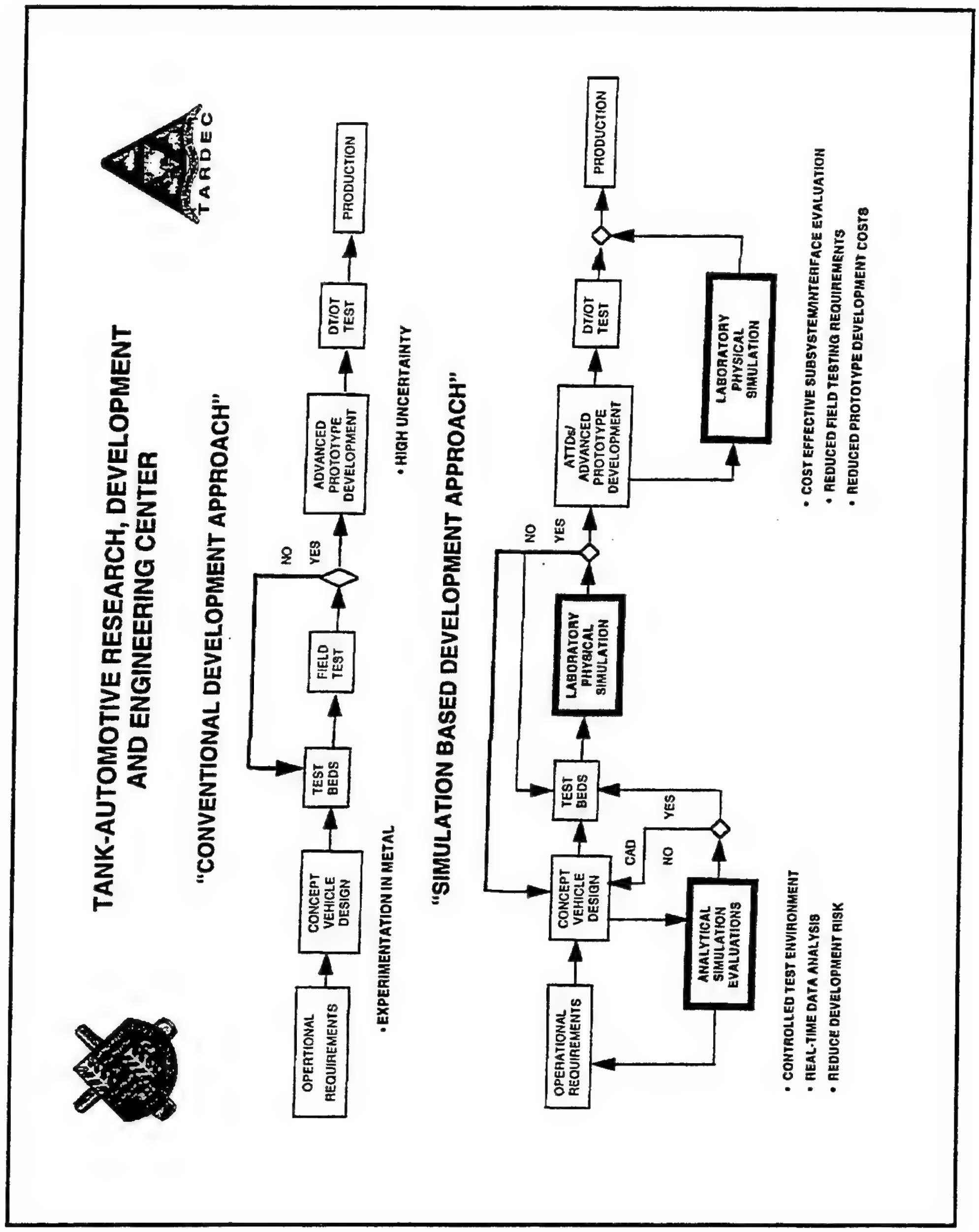
ANALYTICAL SIMULATION

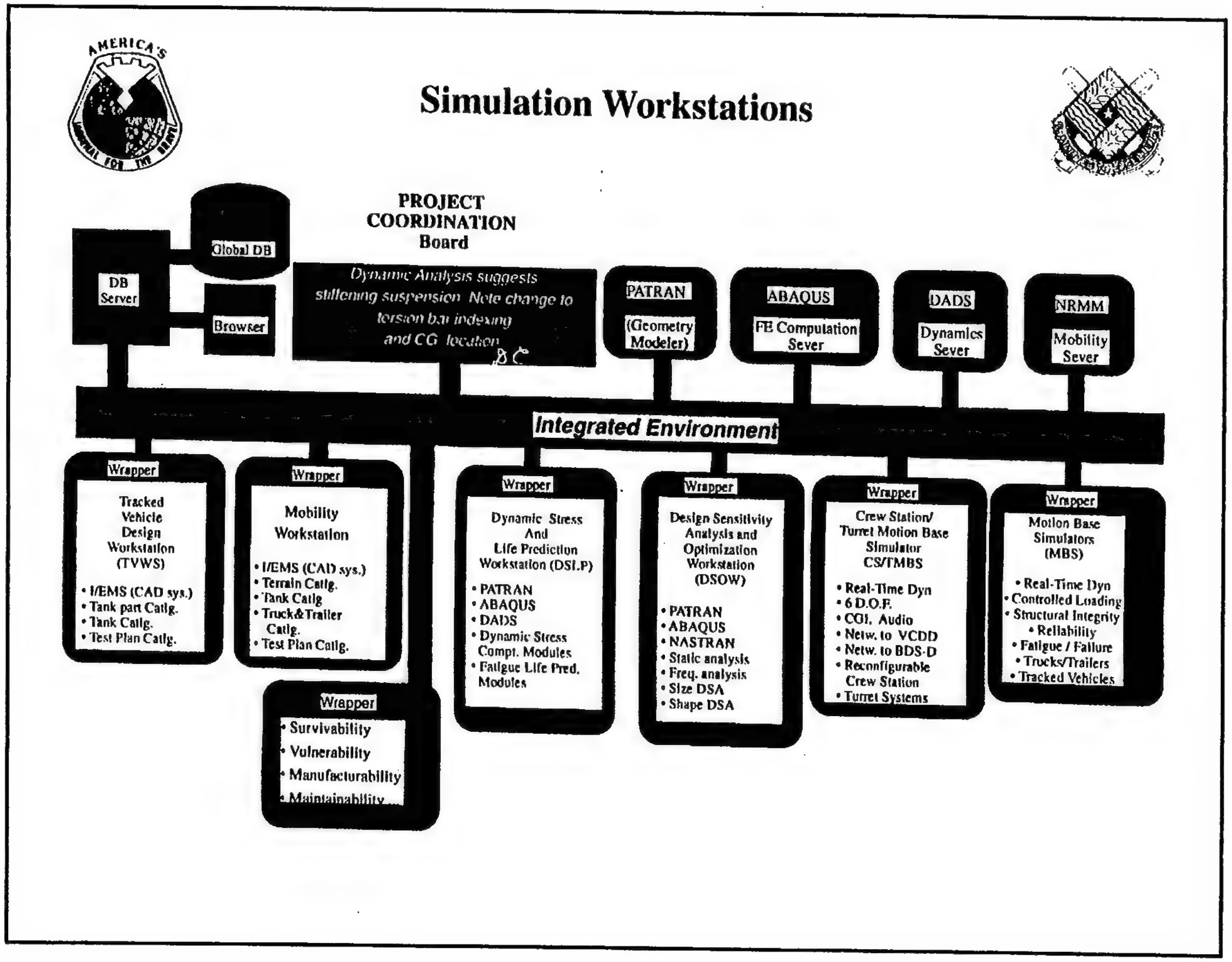
TARDEC

- TOOLS
  - MATHEMATICAL MODELING INCLUDING:
    - Suspension & Propulsion
    - Weapon Stabilization
    - Man-In-The-Loop
    - DIS/DSI Compatability
  - REAL-TIME TOOL DEVELOPMENT
- PURPOSE
  - CONCEPT EVALUATION
  - SYSTEM PERFORMANCE SPECIFICATION
  - TROUBLESHOOT FIELDED VEHICLE PROBLEMS
  - TRADE-OFF ANALYSIS
  - SAFETY STUDIES
  - TEST PLANNING AND EVALUATION

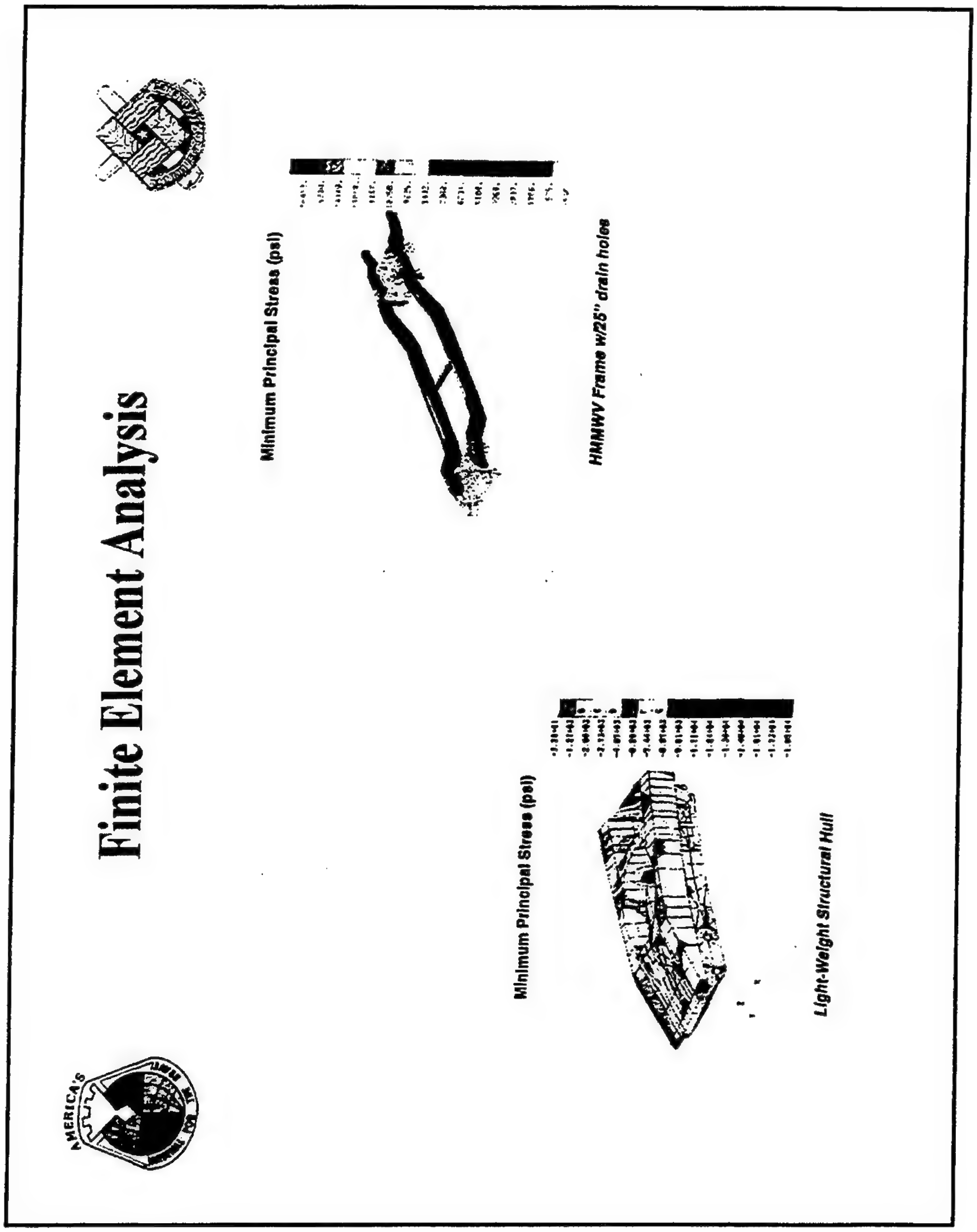
PHYSICAL SIMULATION

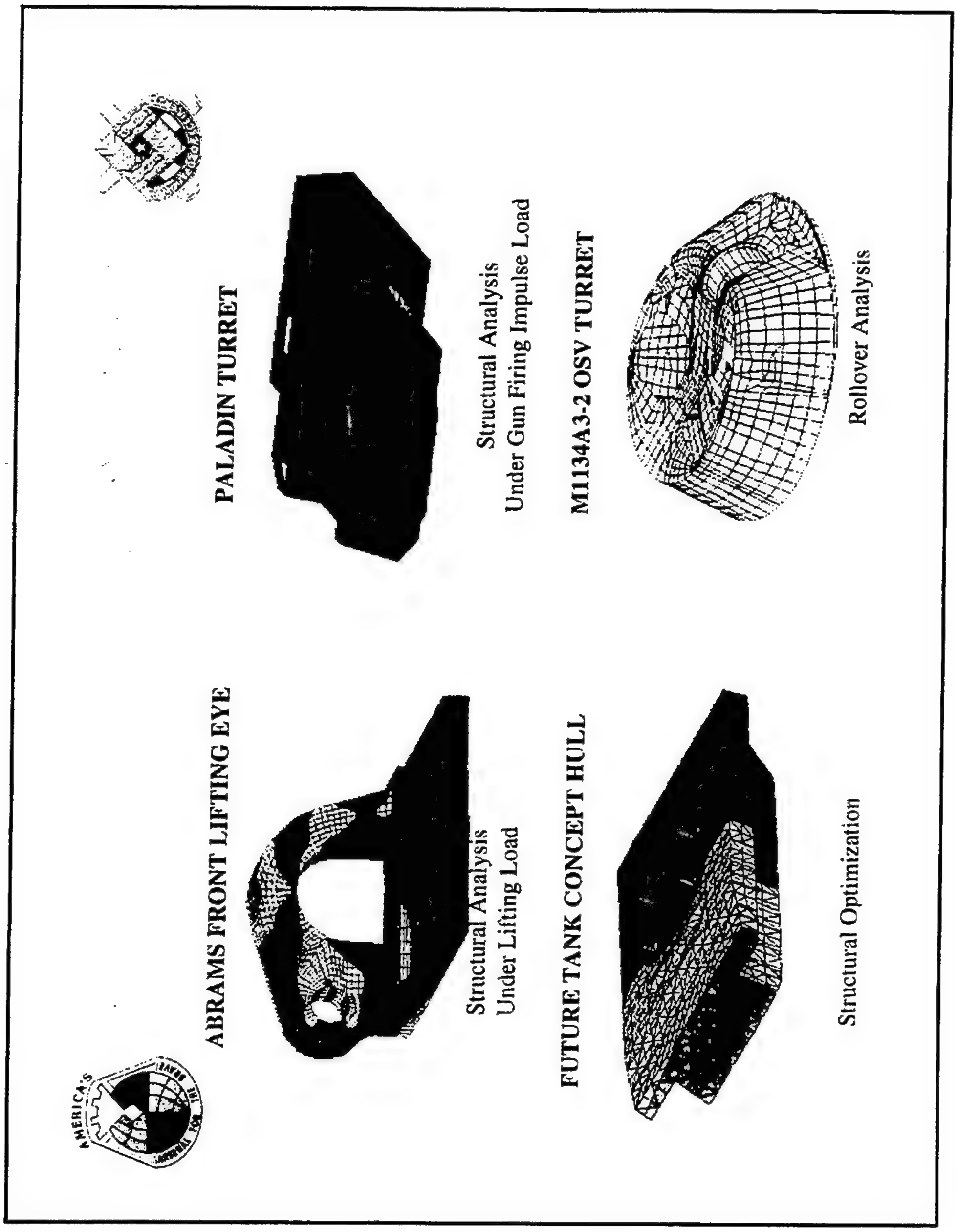
- TOOLS
  - CREW STATION/TURRET MOTION BASE SIMULATOR
  - RIDE MOTION SIMULATOR
  - RECONFIGURABLE MOTION BASE SIMULATORS
  - REAL-TIME COMPUTERS
- PURPOSE
  - DEMONSTRATION/VALIDATION TESTING
    - MAN-IN-THE-LOOP
    - HARDWARE-IN-THE-LOOP
  - ANALYSIS/MODIFICATION OF CURRENT/NEW DESIGNS
  - STRUCTURAL INTEGRITY/RELIABILITY TESTING

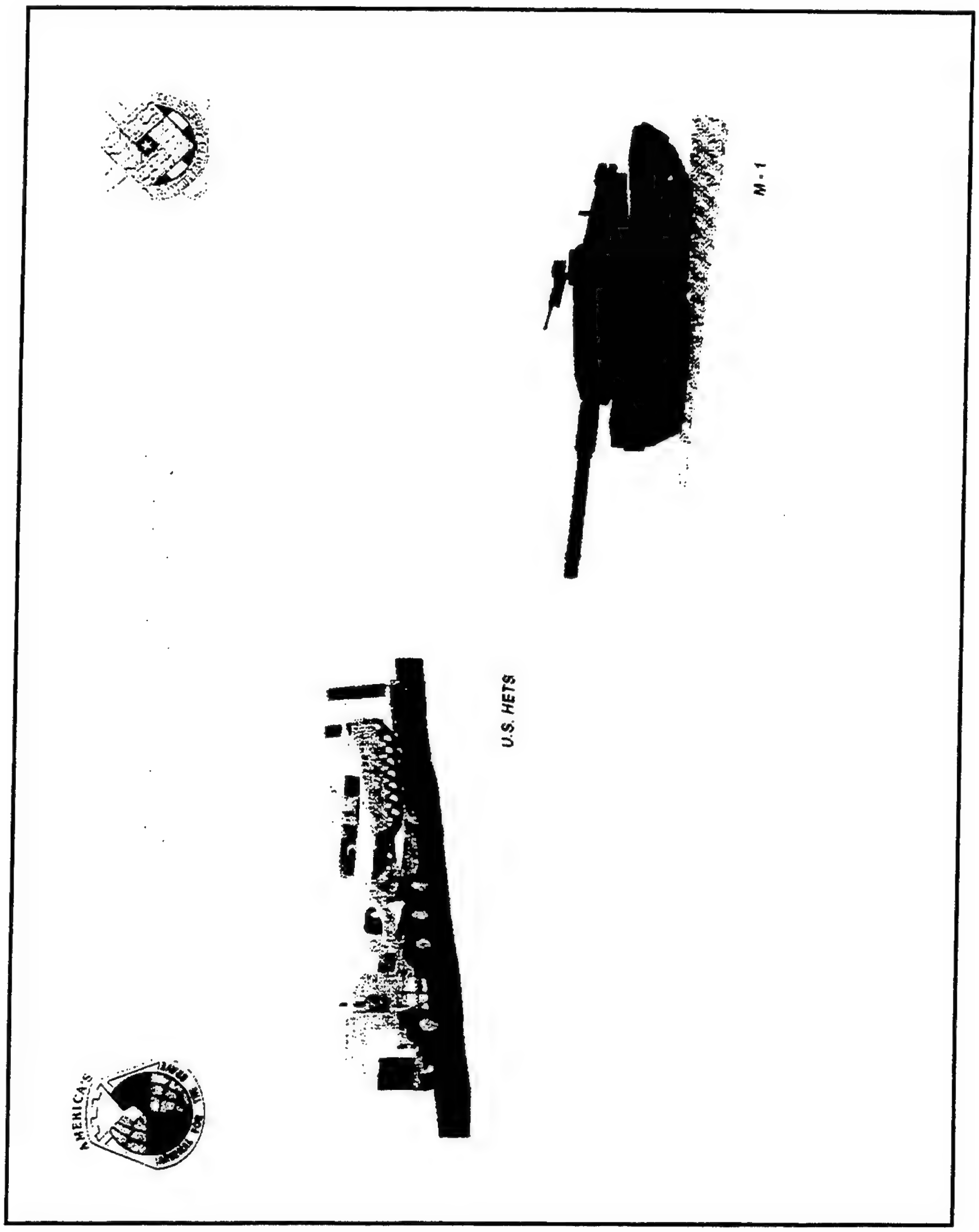

TANK-AUTOMOTIVE RESEARCH, DEVELOPMENT AND ENGINEERING CENTER
TARDEC
"CONVENTIONAL DEVELOPMENT APPROACH"
OPERTIONAL REQUIREMENTS
CONCEPT VEHICLE DESIGN
TEST BEDS
FIELD TEST
NO
YES
ADVANCED PROTOTYPE DEVELOPMENT
DT/OT TEST
PRODUCTION
• EXPERIMENTATION IN METAL
• HIGH UNCERTAINTY
"SIMULATION BASED DEVELOPMENT APPROACH"
OPERATIONAL REQUIREMENTS
CONCEPT VEHICLE DESIGN
ANALYTICAL SIMULATION EVALUATIONS
CAD
NO
YES
TEST BEDS
LABORATORY PHYSICAL SIMULATION
NO
YES
ATTDs/ ADVANCED PROTOTYPE DEVELOPMENT
DT/OT TEST
LABORATORY PHYSICAL SIMULATION
PRODUCTION
• CONTROLLED TEST ENVIRONMENT
• REAL-TIME DATA ANALYSIS
• REDUCE DEVELOPMENT RISK
• COST EFFECTIVE SUBSYSTEM/INTERFACE EVALUATION
• REDUCED FIELD TESTING REQUIREMENTS
• REDUCED PROTOTYPE DEVELOPMENT COSTS

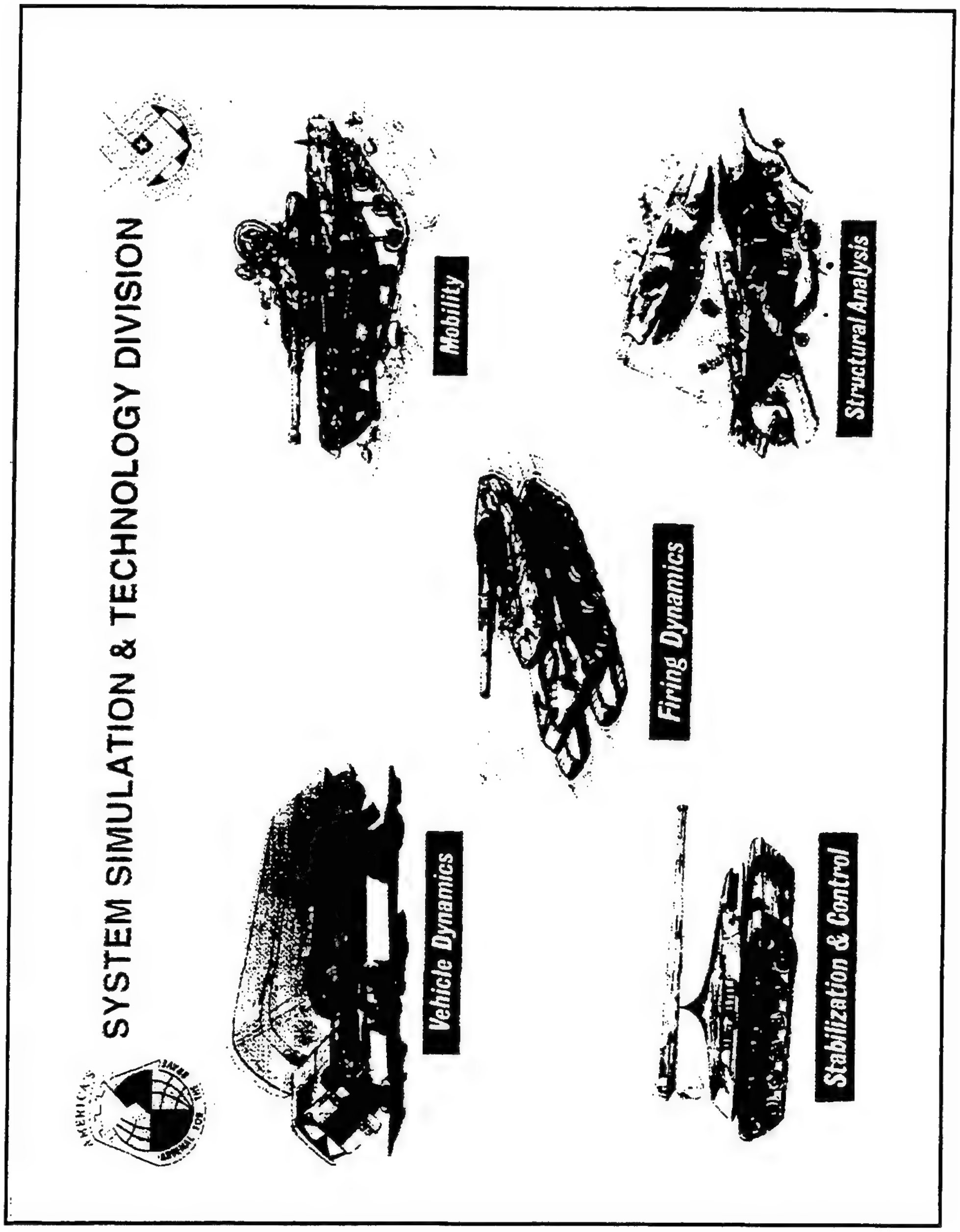


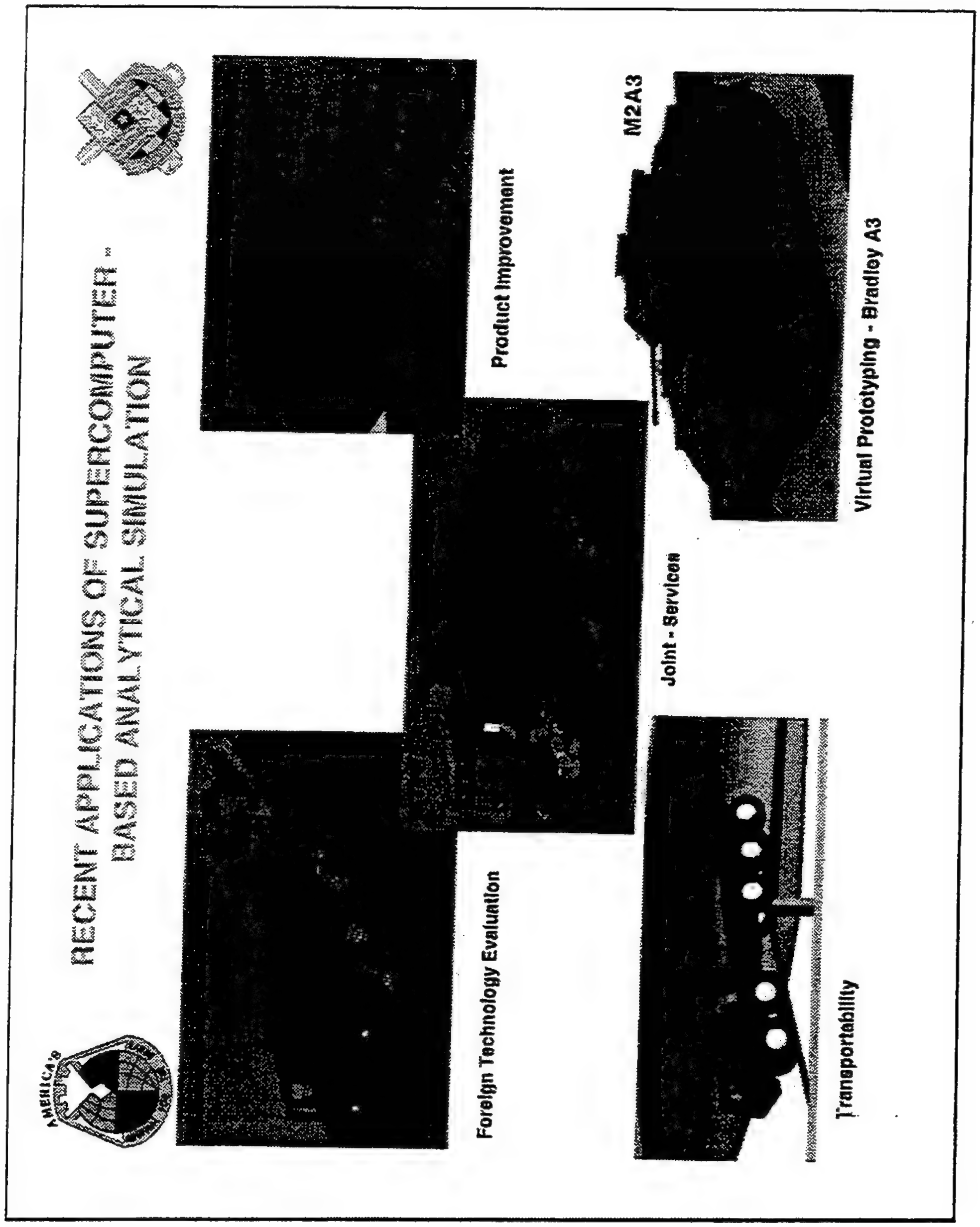
Simulation Workstations
PROJECT COORDINATION Board
Dynamic Analysis suggests stiffening suspension. Note change to torsion bar indexing and CG location
DB Server
Global DB
Browser
PATRAN
(Geometry Modeler)
ABAQUS
FE Computation Sever
DADS
Dynamics Sever
NRMM
Mobility Sever
Integrated Environment
Wrapper
Tracked Vehicle Design Workstation (TVWS)
• I/EMS (CAD sys.)
• Tank part Catlg.
• Tank Catlg.
• Test Plan Catlg.
Wrapper
Mobility Workstation
• I/EMS (CAD sys.)
• Terrain Catlg.
• Tank Catlg
• Truck&Trailer Catlg.
• Test Plan Catlg.
Wrapper
• Survivability
• Vulnerability
• Manufacturability
• Maintainability
Wrapper
Dynamic Stress And Life Prediction Workstation (DSLP)
• PATRAN
• ABAQUS
• DADS
• Dynamic Stress Compt. Modules
• Fatigue Life Pred. Modules
Wrapper
Design Sensitivity Analysis and Optimization Workstation (DSOW)
• PATRAN
• ABAQUS
• NASTRAN
• Static analysis
• Freq. analysis
• Size DSA
• Shape DSA
Wrapper
Crew Station/ Turret Motion Base Simulator CS/TMBS
• Real-Time Dyn
• 6 D.O.F.
• COI. Audio
• Netw. to VCDD
• Netw. to BDS-D
• Reconfigurable Crew Station
• Turret Systems
Wrapper
Motion Base Simulators (MBS)
• Real-Time Dyn
• Controlled Loading
• Structural Integrity
• Reliability
• Fatigue / Failure
• Trucks/Trailers
• Tracked Vehicles


Finite Element Analysis
Minimum Principal Stress (psi)
HMMWV Frame w/25" drain holes
Minimum Principal Stress (psi)
Light-Weight Structural Hull
AMERICA'S

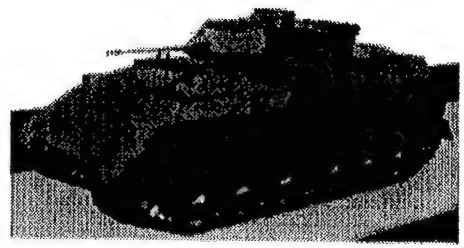

ABRAMS FRONT LIFTING EYE
Structural Analysis
Under Lifting Load
PALADIN TURRET
Structural Analysis
Under Gun Firing Impulse Load
FUTURE TANK CONCEPT HULL
Structural Optimization
M1134A3-2 OSV TURRET
Rollover Analysis


U.S. HETS
M-1


SYSTEM SIMULATION & TECHNOLOGY DIVISION
Vehicle Dynamics
Mobility
Firing Dynamics
Stabilization & Control
Structural Analysis


RECENT APPLICATIONS OF SUPERCOMPUTER -
BASED ANALYTICAL SIMULATION
AMERICA'S
Foreign Technology Evaluation
Product Improvement
Joint - Services
M2A3
Transportability
Virtual Prototyping - Bradley A3

SYSTEM SIMULATION & TECHNOLOGY DIVISION
VIRTUAL PROTOTYPING - BRADLEY A3



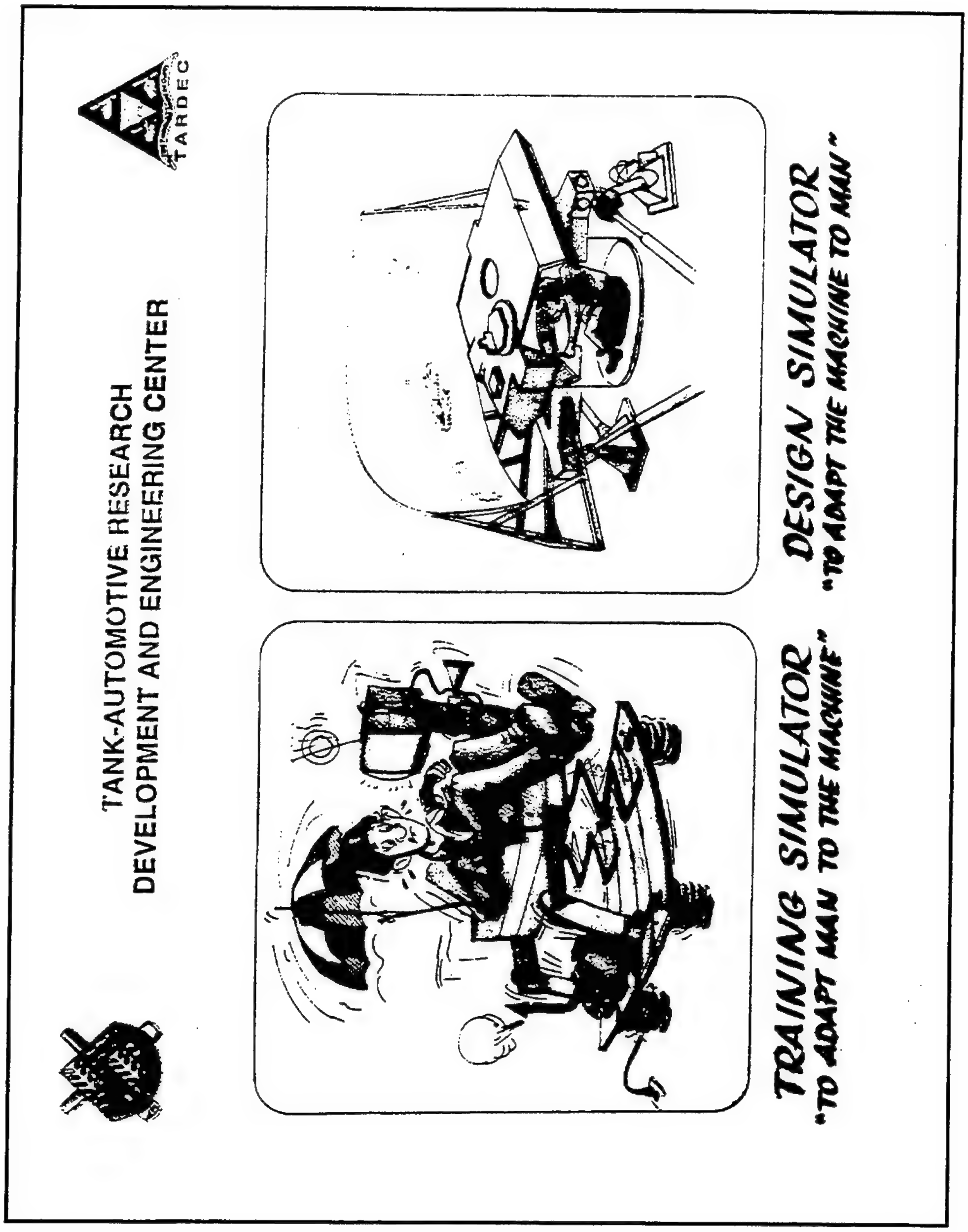
- Develop real-time dynamic model including:
  - Propulsion system
  - Weapon stabilization system
- Install model on the DSI to increase the realism of the war-gaming on the network.
- Benchmark A2 weapon system for A3 upgrade using the CS/TMBS.
- Examine how upweighting affects suspension and structural integrity using the reconfigurable motion base simulator.

TANK-AUTOMOTIVE RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

TARDEC

TEST PLANNING AND VALIDATION

- SIMULATION AIDS TO TEST PLANNING
  - DEFINE TEST ENVIRONMENTS
  - DEFINE DATA/INSTRUMENTATION REQUIREMENTS
  - IDENTIFY POTENTIAL PROBLEMS/FAILURE MODES
  - FOCUS TESTING ON AREAS OF CONCERN
  - REDUCE TESTING TO SPOT-CHECKING IN AREAS OF CONFIDENCE TO REDUCE COSTS
- VALIDATION
  - VALIDATE MODELS FOR USE IN PROBLEM SOLVING AND FUTURE PRODUCT IMPROVEMENTS
  - ENLARGE DATABASE ON VEHICLE FLEET
  - INCREASE CONFIDENCE IN FUTURE USE OF SIMULATION


TANK-AUTOMOTIVE RESEARCH
DEVELOPMENT AND ENGINEERING CENTER
TARDEC
TRAINING SIMULATOR
"TO ADAPT MAN TO THE MACHINE"
DESIGN SIMULATOR
"TO ADAPT THE MACHINE TO MAN"

TANK-AUTOMOTIVE RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

TARDEC

"ATTRIBUTES"

	FIELD TESTING	MOTION BASE SIMULATION
WIDE VARIETY OF TEST COURSES		X
MAINTENANCE FREE TEST COURSES		X
PRIME MOVER NOT REQUIRED		X
WEATHER INDEPENDENT		X
REPEATABLE		X
OBSERVABLE		X
DRIVER INDEPENDENT		X
TEST RESULTS AVAILABLE EARLY IN DEVELOPMENT		X
UNLIMITED TEST SCOPE	X	
ENVIRONMENTAL INFLUENCE	X	

TANK-AUTOMOTIVE RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

TARDEC

INDUSTRY USE

- VIA EXISTING TACOM CONTRACT
- VIA REQUEST DIRECTLY FROM INDUSTRY
  - CONTACT ENGINEER
  - WRITE TEST PLAN
  - PRESENT TO CONTRACTS AND LEGAL OFFICES
  - WRITE LETTER REQUESTING PERMISSION TO TACOM CG
  - SIGN CONTRACT AND PROVIDE FUNDS
- MAKE MOTION BASE SIMULATION A REQUIREMENT IN CONTRACTS
- COOPERATIVE RESEARCH AND DEVELOPMENT AGREEMENTS (CRADAs)

LABORATORY IMPROVEMENTS

TARDEC

- ON-GOING
  - CS/TMBS CONTROLLER UPGRADE
  - NEW COMPUTER GENERATED IMAGERY SYSTEM
  - NEW RIDE MOTION SIMULATOR
  - HYDRAULIC POWER SUPPLY STUDY & RECOMMENDATION
  - AUDIO GENERATION SYSTEM
  - REAL-TIME SIMULATOR/SIMULATION INTERACTION
- FUTURE
  - HYDRAULIC POWER SUPPLY UPGRADE
  - MOVING TARGET SIMULATOR
  - INTEGRATED SIMULATOR TEST AND DIAGNOSTIC FUNCTION
  - MULTI-AXIAL SPINDLE COUPLED MOTION SIMULATORS
- GOAL
  - MOTION BASED, MAN-IN-THE-LOOP VIRTUAL PROVING GROUND FOR DESIGN OPTIMIZATION AND ANALYSIS

TANK-AUTOMOTIVE RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

TARDEC

CAPABILITIES AVAILABLE

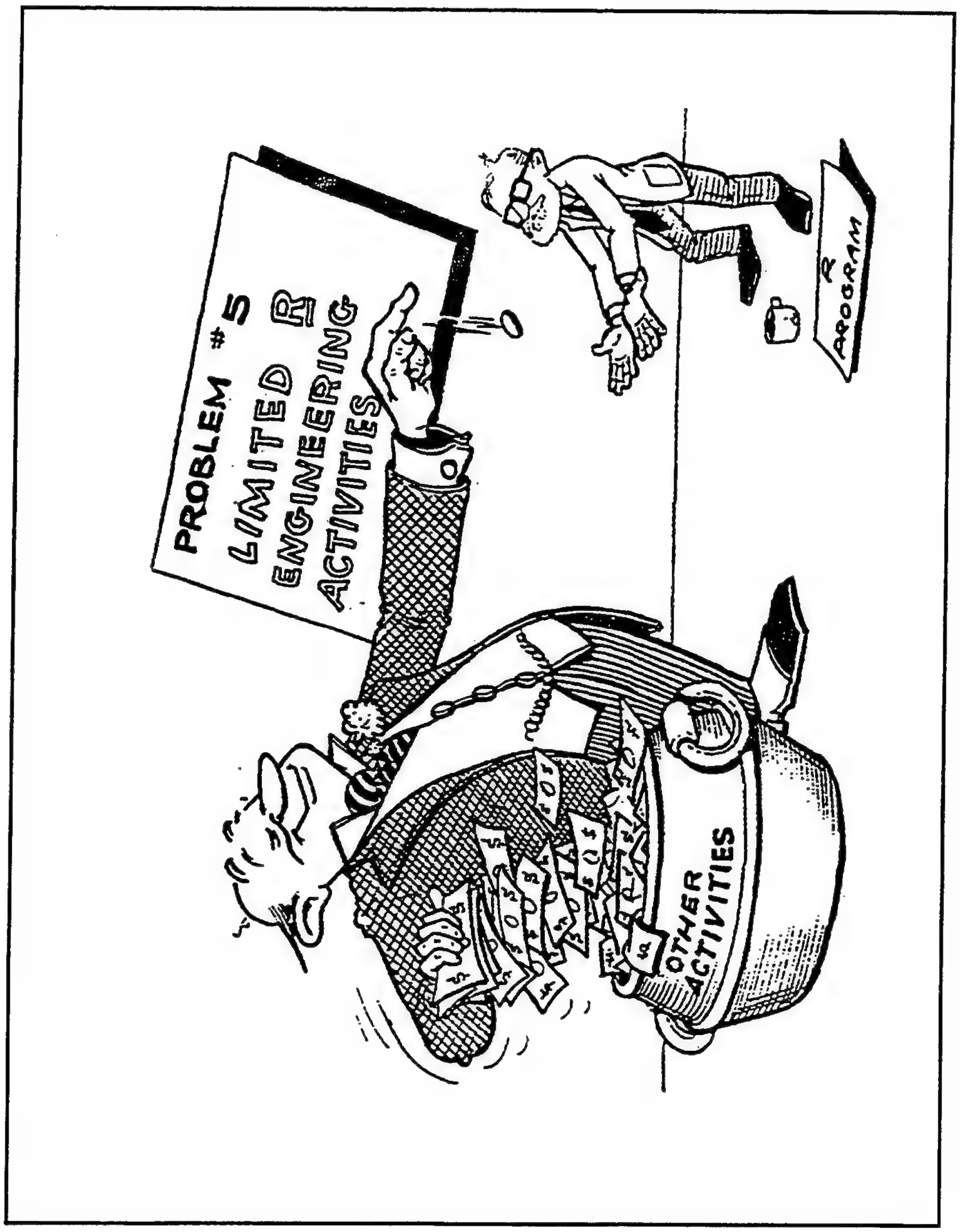
- MOTION CONTROL SYSTEMS:
  - COMPUTER AUTOMATED MEASUREMENT AND CONTROL (CAMAC) IEEE-583
  - CRAY-2 BASED DYNAMIC SIMULATIONS
  - $MATRIX_X$ BASED CONTROL SYSTEM SYNTHESIS
- DATA ACQUISITION:
  - GYROS, ACCELEROMETERS, LVDTs, STRAIN GAGES, AND STRING POTS
  - DATA DIGITALLY RECORDED
  - REAL-TIME ACQUISITION AND ANALYSIS
- DATA ANALYSIS:
  - PLOTTING (TIME HISTORIES, HISTOGRAMS, PARAMETRIC)
  - FREQUENCY ANALYSIS (FFT, BODE, AND NYQUIST)
- ACCESS TO ANALYSIS SPECIALISTS (STRUCTURES, DYNAMICS, CONTROLS)

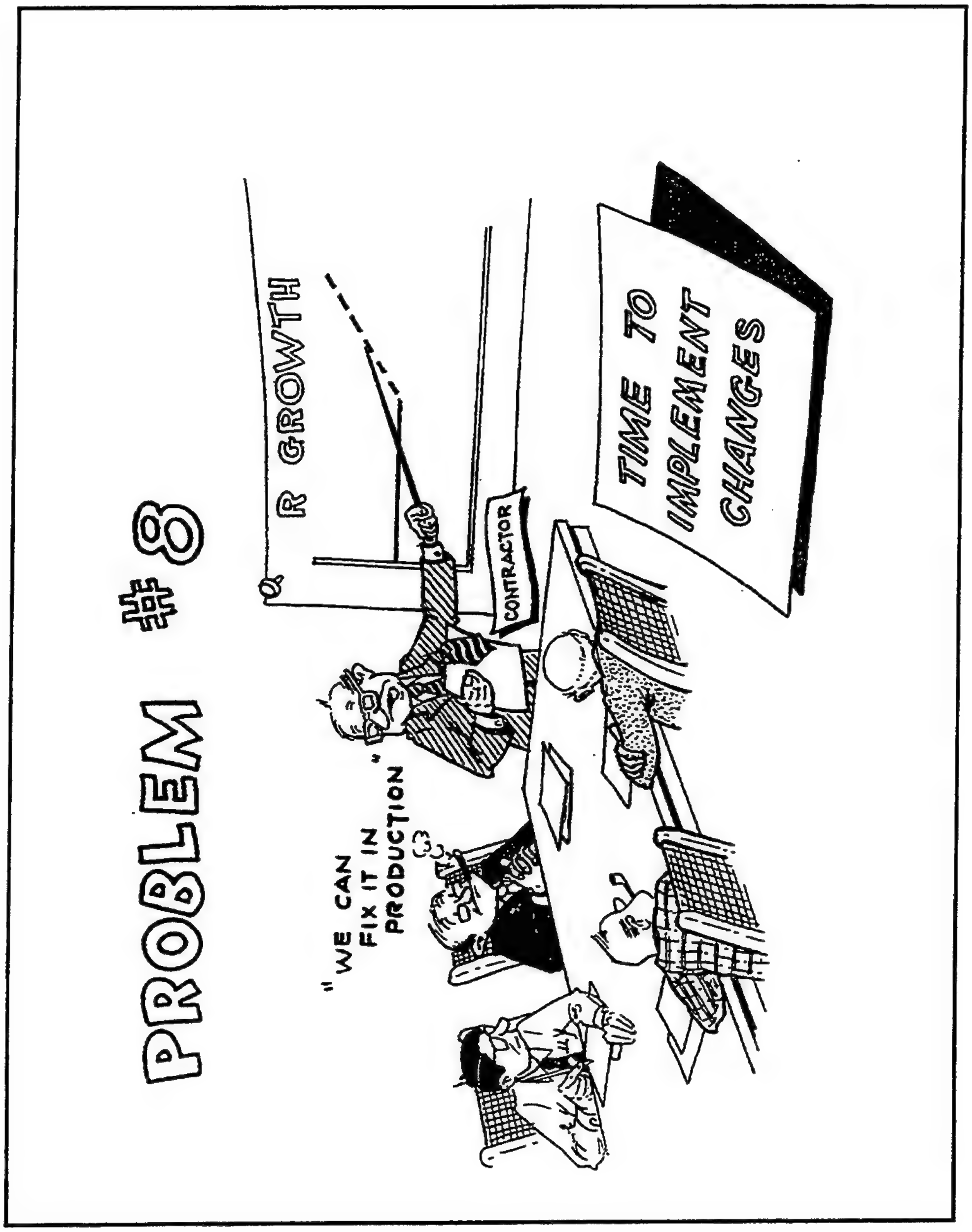
Virtual RAM

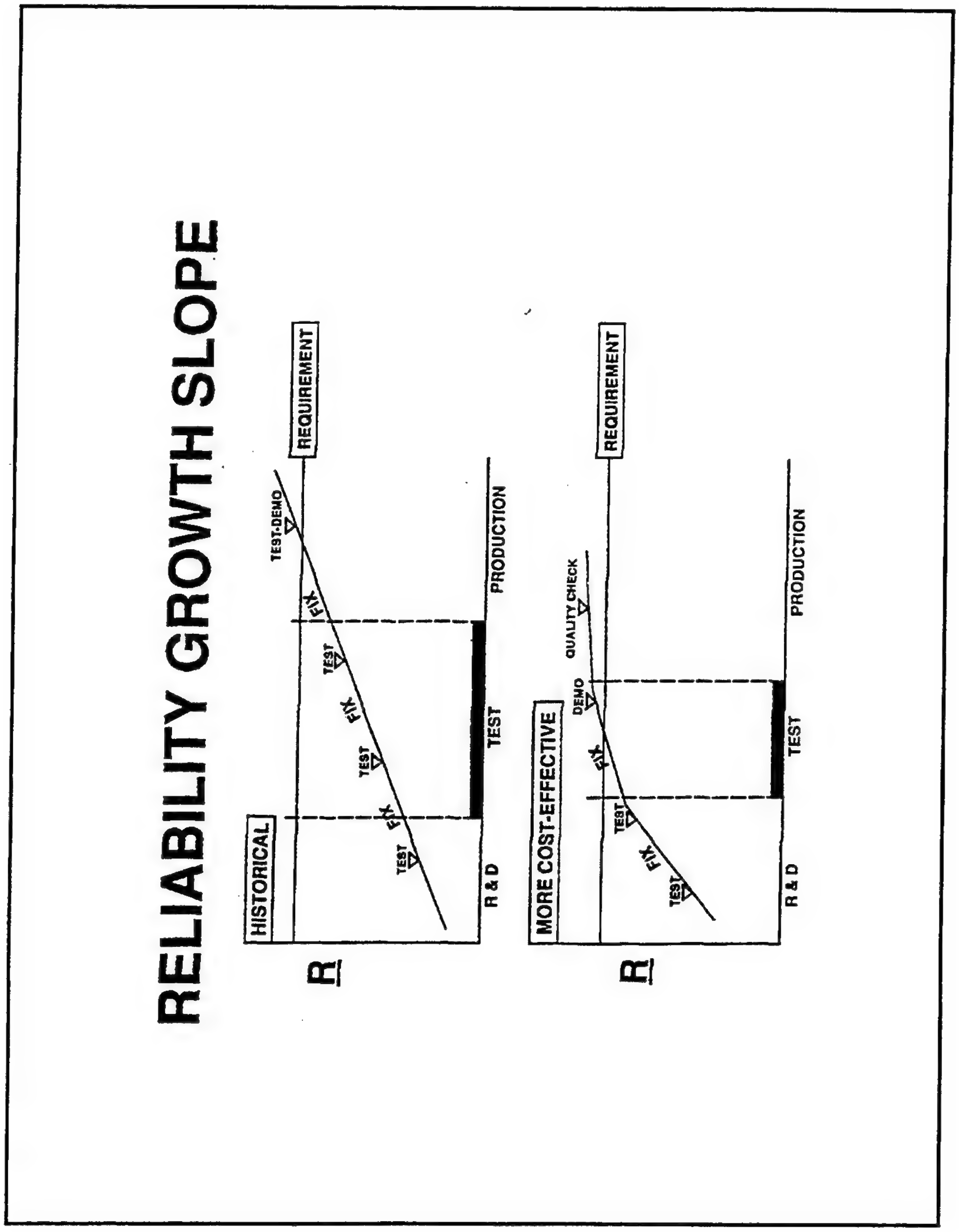
March 1996

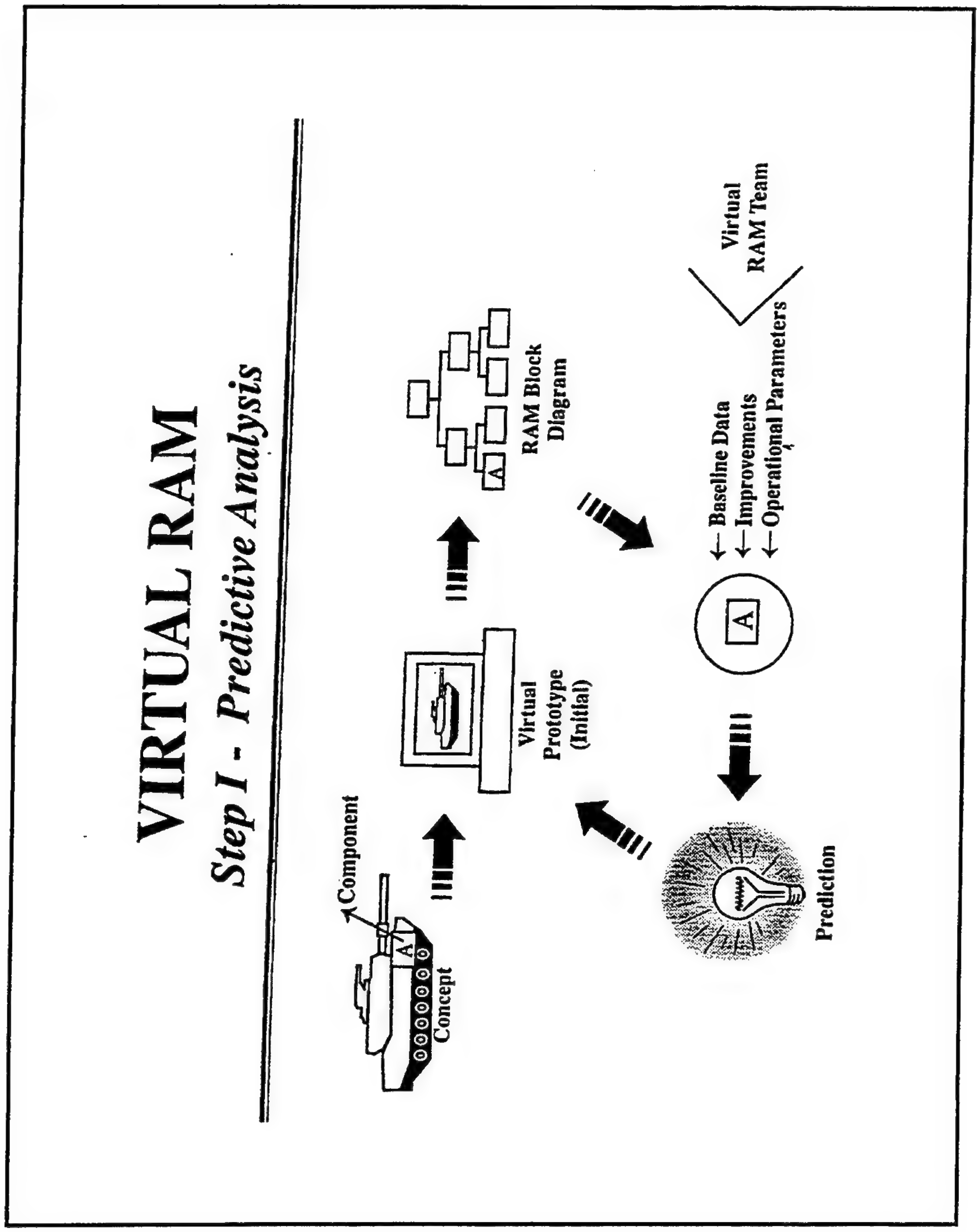
PRESENTED BY:

MR. L. K. JOKUBAITIS
Associate Director
Development Business Group
TARDEC/TACOM


PROBLEM #5
LIMITED R
ENGINEERING
ACTIVITIES
OTHER ACTIVITIES
R PROGRAM

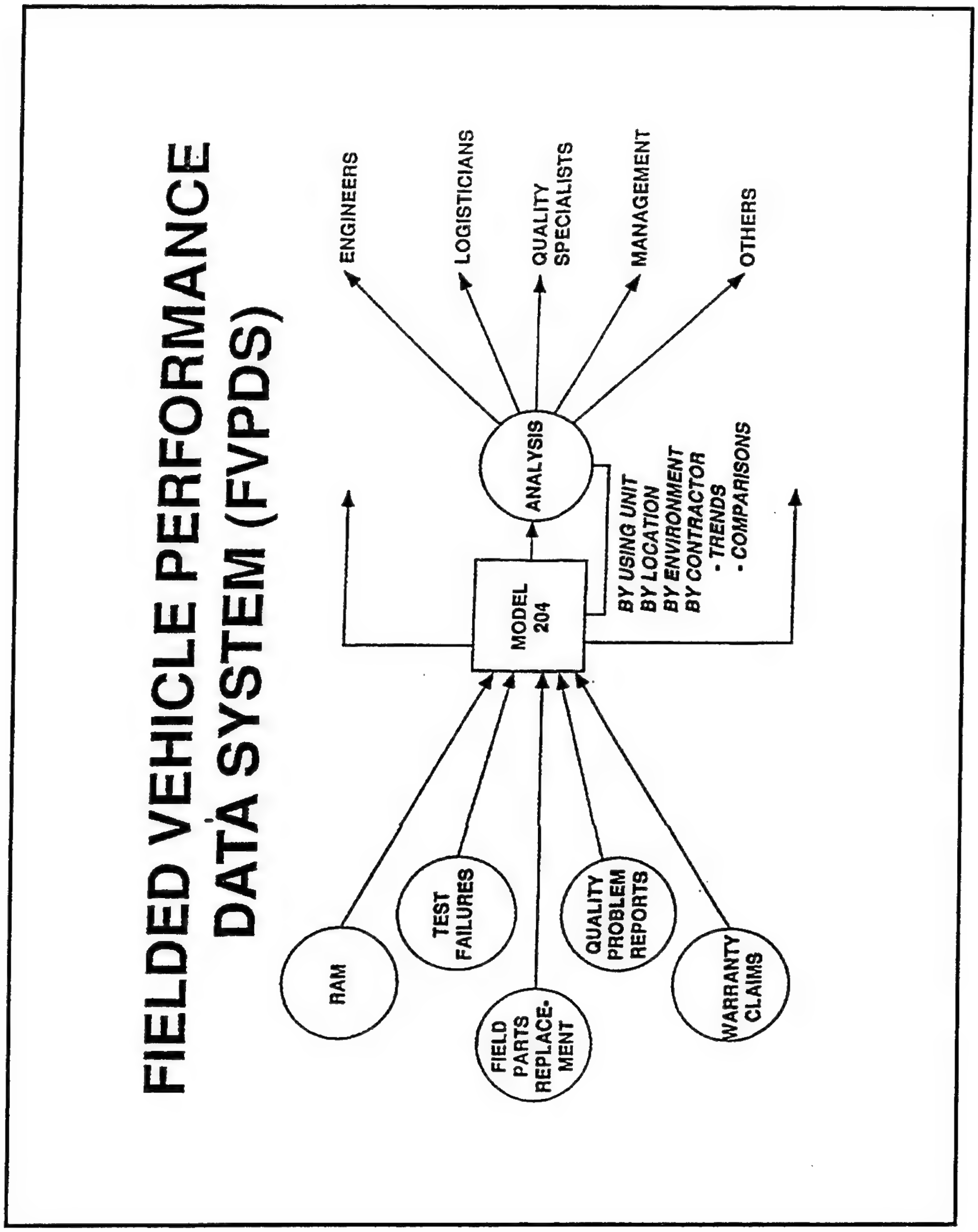

PROBLEM #8
R GROWTH
CONTRACTOR
"WE CAN FIX IT IN PRODUCTION"
TIME TO IMPLEMENT CHANGES

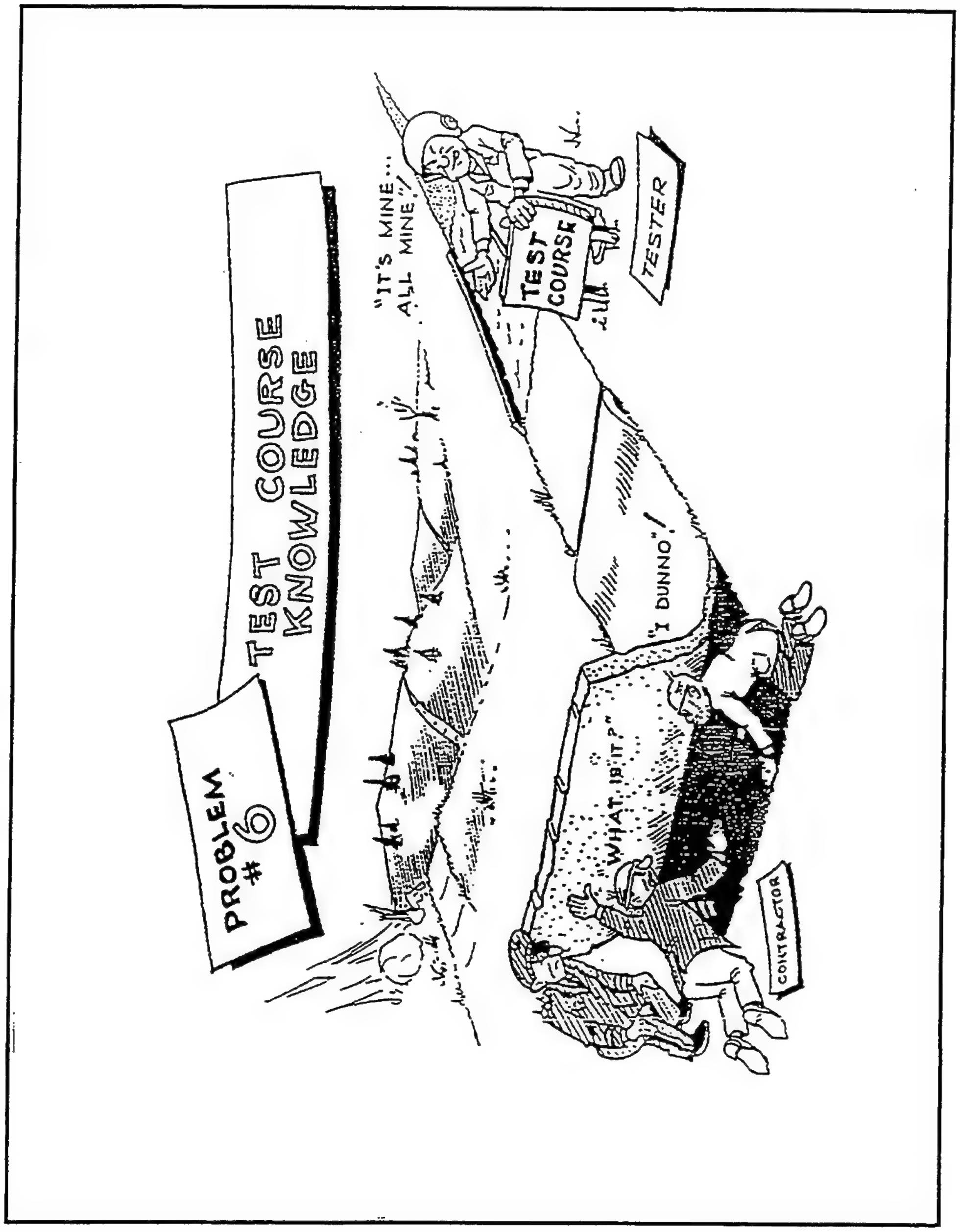

RELIABILITY GROWTH SLOPE
HISTORICAL
R
REQUIREMENT
TEST
FIX
TEST
FIX
TEST
FIX
TEST-DEMO
R & D
TEST
PRODUCTION
MORE COST-EFFECTIVE
R
REQUIREMENT
TEST
FIX
TEST
FIX
DEMO
QUALITY CHECK
R & D
TEST
PRODUCTION

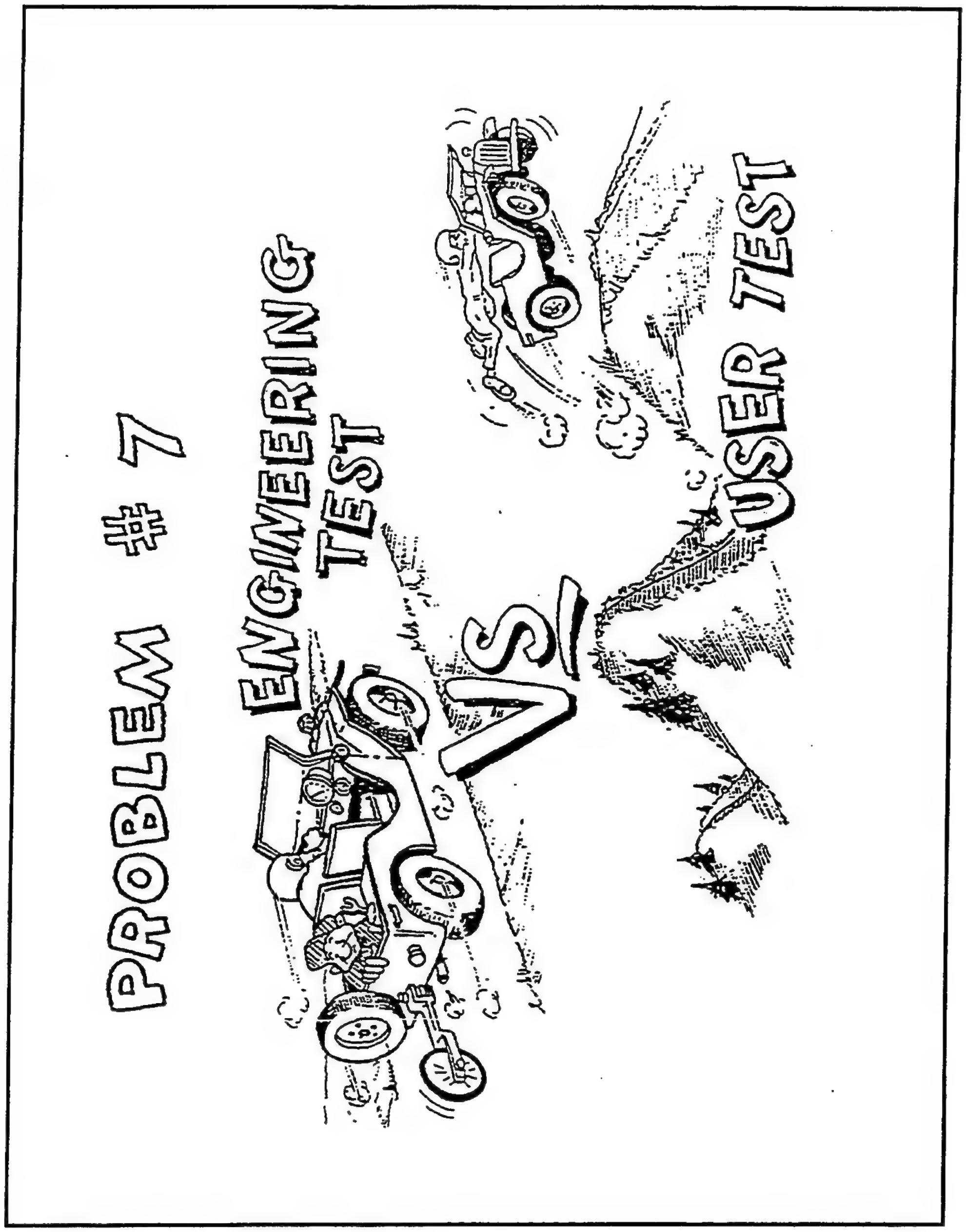

VIRTUAL RAM
Step I - Predictive Analysis
Component
A
Concept
Virtual
Prototype
(Initial)
A
RAM Block
Diagram
A
← Baseline Data
← Improvements
← Operational Parameters
Virtual
RAM Team
Prediction

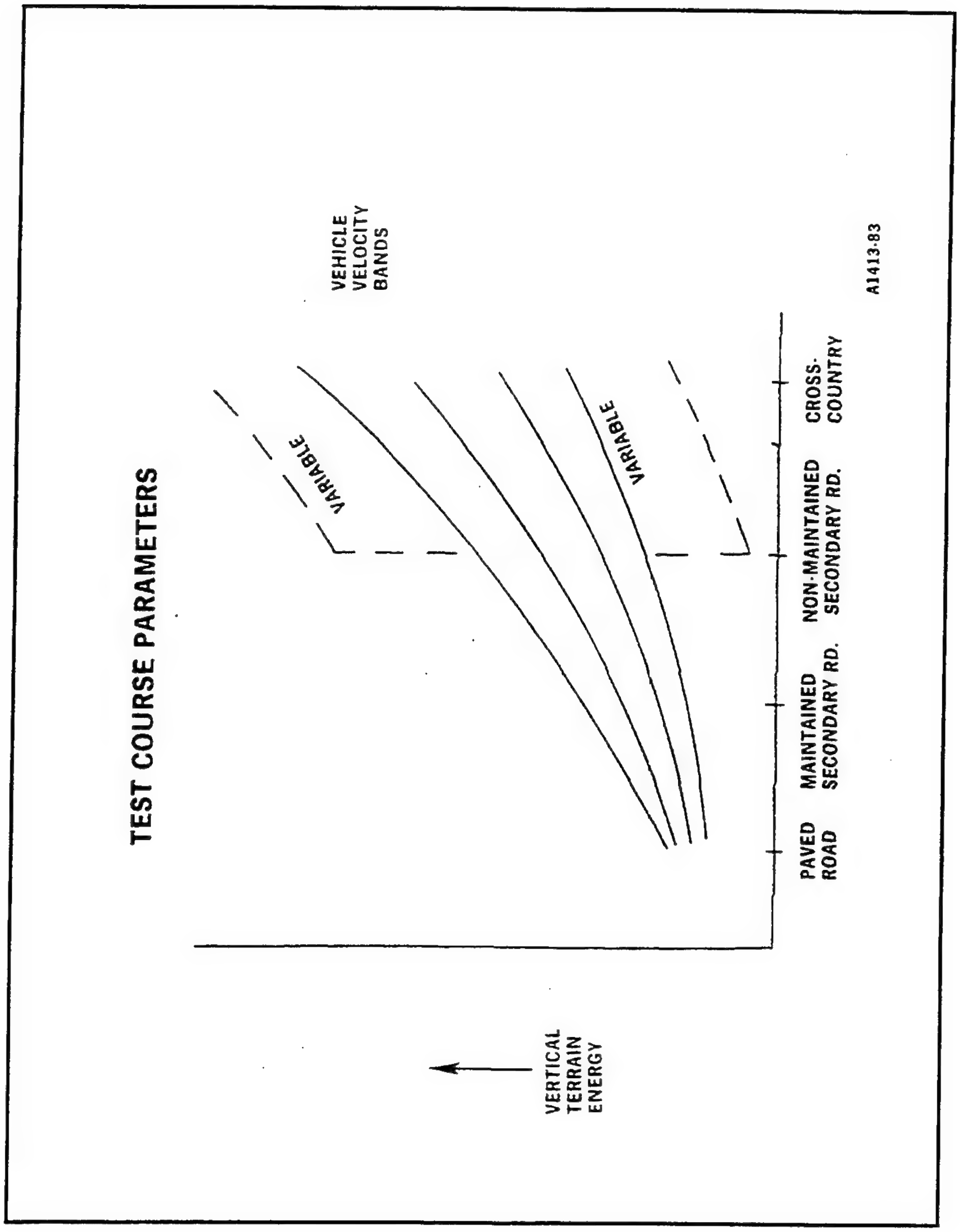
M1A1 BASELINE RAM DATA

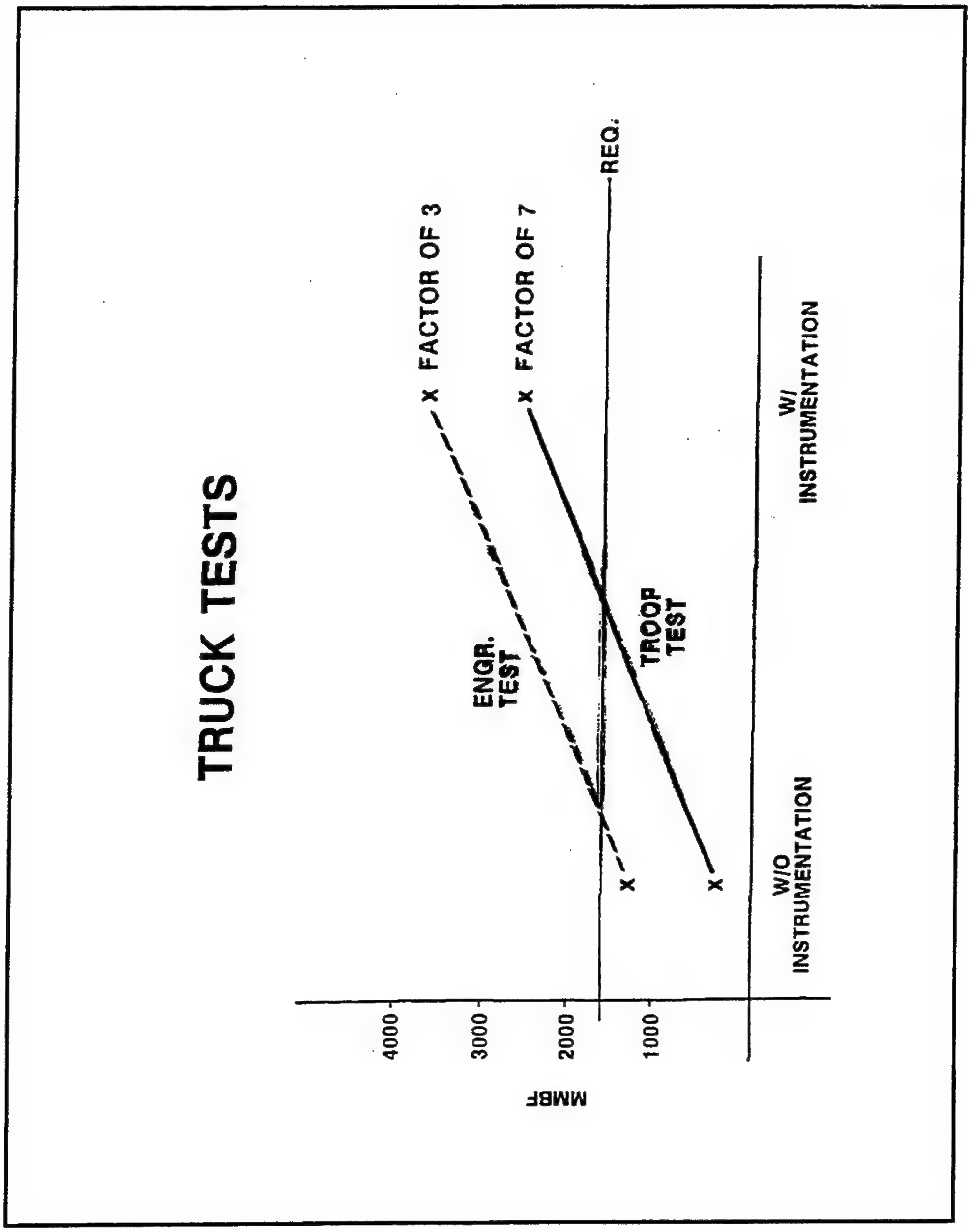
SUBSYSTEM	FAIL RATE M1A1 UMA/MILE X(.001)	MTTR M1A1 HOUR	MR M1A1 X(.01)
ALTERNATOR	0.3	5.7	1.5
REGULATOR	0.1	4.2	0.1
BATTERIES	0.8	0.7	0.6
STARTER	0.2	3.3	0.6
DRIVER'S MASTER PANEL	0.3	0.4	0.1
SHOCK ABSORBER	**0.8**	**7.3**	**5.8**
LINK ASSEMBLIES	0.6	2.8	1.7
END CONNECTORS	6.4	0.4	2.5
CENTER GUIDES, CAPS & BOLTS	0.4	0.7	0.2
TRACK MISCELLANEOUS	1.7	6.8	11.6
ENGINE BLOCK	COVERED ELSEWHERE ON M1A1		
ACCESSORY GEARBOX MODULE	0.1	15.3	0.4
FORWARD ENGINE MODULE	0.7	3.8	2.6
REAR ENGINE MODULE	0.1	22.4	3.3
ENGINE ACCESSORIES	0.7	3.6	2.6
ENGINE MISCELLANEOUS	1.2	2.0	2.5


FIELDED VEHICLE PERFORMANCE
DATA SYSTEM (FVPDS)
RAM
TEST FAILURES
FIELD PARTS REPLACE-MENT
QUALITY PROBLEM REPORTS
WARRANTY CLAIMS
MODEL 204
ANALYSIS
BY USING UNIT
BY LOCATION
BY ENVIRONMENT
BY CONTRACTOR
- TRENDS
- COMPARISONS
ENGINEERS
LOGISTICIANS
QUALITY SPECIALISTS
MANAGEMENT
OTHERS


PROBLEM # 6
TEST COURSE KNOWLEDGE
"IT'S MINE... ALL MINE"
TEST COURSE
TESTER
"I DUNNO"!
"WHAT IS IT?"
CONTRACTOR


PROBLEM # 7
ENGINEERING TEST
VS
USER TEST


TEST COURSE PARAMETERS
VERTICAL TERRAIN ENERGY
VARIABLE
VARIABLE
VEHICLE VELOCITY BANDS
PAVED ROAD
MAINTAINED SECONDARY RD.
NON-MAINTAINED SECONDARY RD.
CROSS-COUNTRY
A1413-83


TRUCK TESTS
MMBF
4000
3000
2000
1000
ENGR.
TEST
TROOP
TEST
FACTOR OF 3
FACTOR OF 7
REQ.
W/O
INSTRUMENTATION
W/
INSTRUMENTATION

TRUCK TEST RESULT

ANALYSIS

DESIGN FACTOR X TERRAIN FACTOR X DRIVER FACTOR ⟶ RELIABILITY

	(ENERGY)				(SPEED & DISCIPLINE)	
ENG. TESTS:	1.5	X	1.0	X	2.0	⟶ 3*
TROOP TESTS:	1.5	X	2.0	X	2.3	⟶ 7*

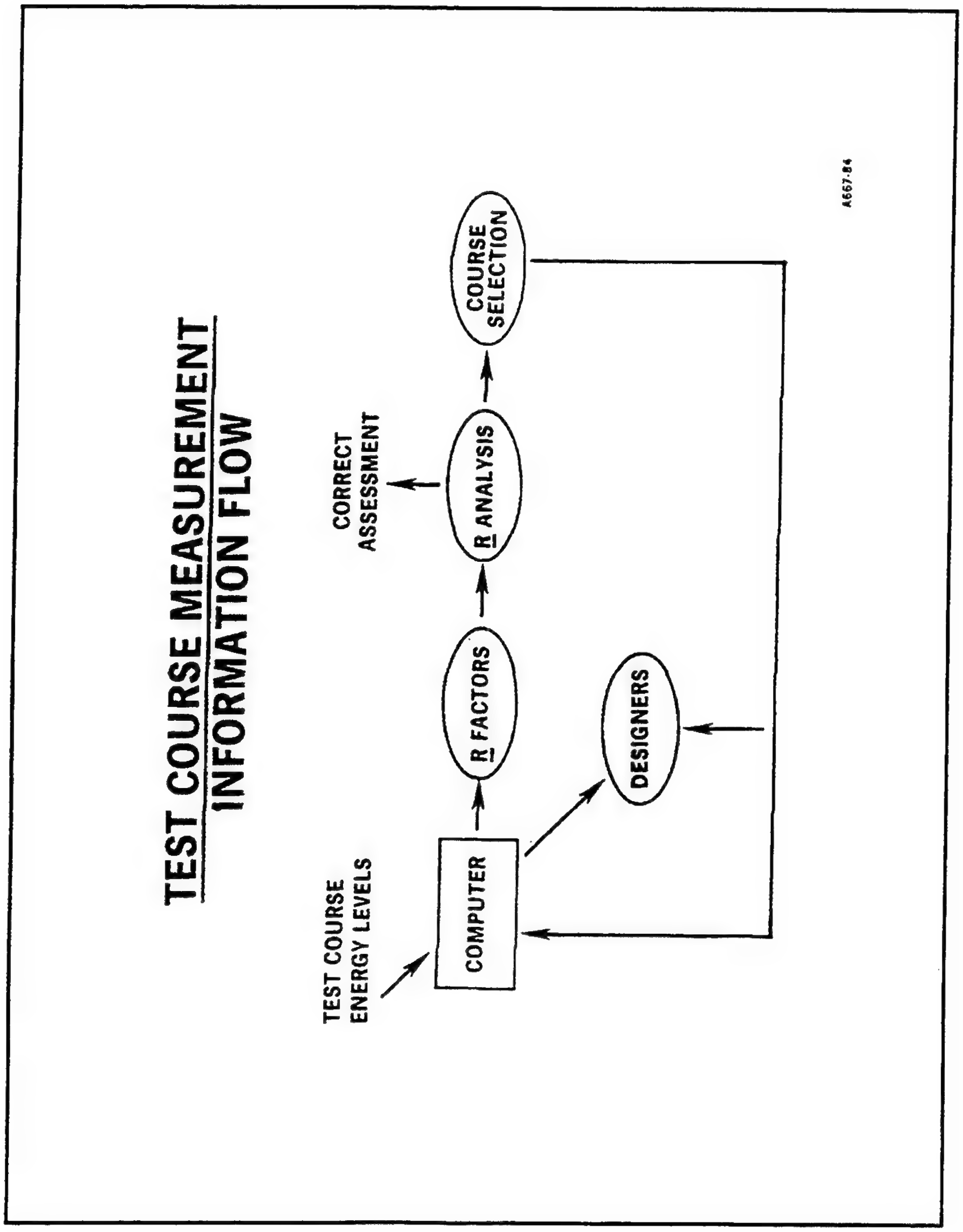
*ESTIMATES FOR DEMONSTRATION PURPOSE

A-4871

THE NEED

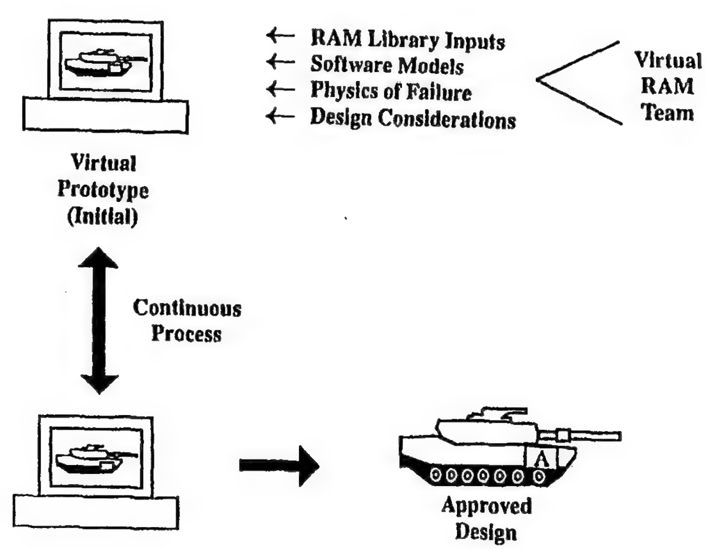
- RELATE VEHICLE REQUIREMENTS TO STRESS LEVELS
  - — VEHICLE SYSTEM/COMPONENT (VIBRATIONAL, TORSIONAL)
  - — DRIVE TRAIN (POWER, TORQUE, SHOCK LOADING)
- METHODOLOGY/EQUIPMENT FOR MEASURING TEST COURSE SEVERITY
  - — PROFILE
  - — TERRAIN (STRENGTH AND COMPOSITION)
- CORRELATION OF TERRAIN AND VEHICLE SPEED TO VEHICLE/COMPONENT STRESS LEVELS

A1422-83


TEST COURSE MEASUREMENT
INFORMATION FLOW
TEST COURSE ENERGY LEVELS
COMPUTER
R FACTORS
R ANALYSIS
CORRECT ASSESSMENT
COURSE SELECTION
DESIGNERS
A667-84

VIRTUAL RAM

Step II - Development Process



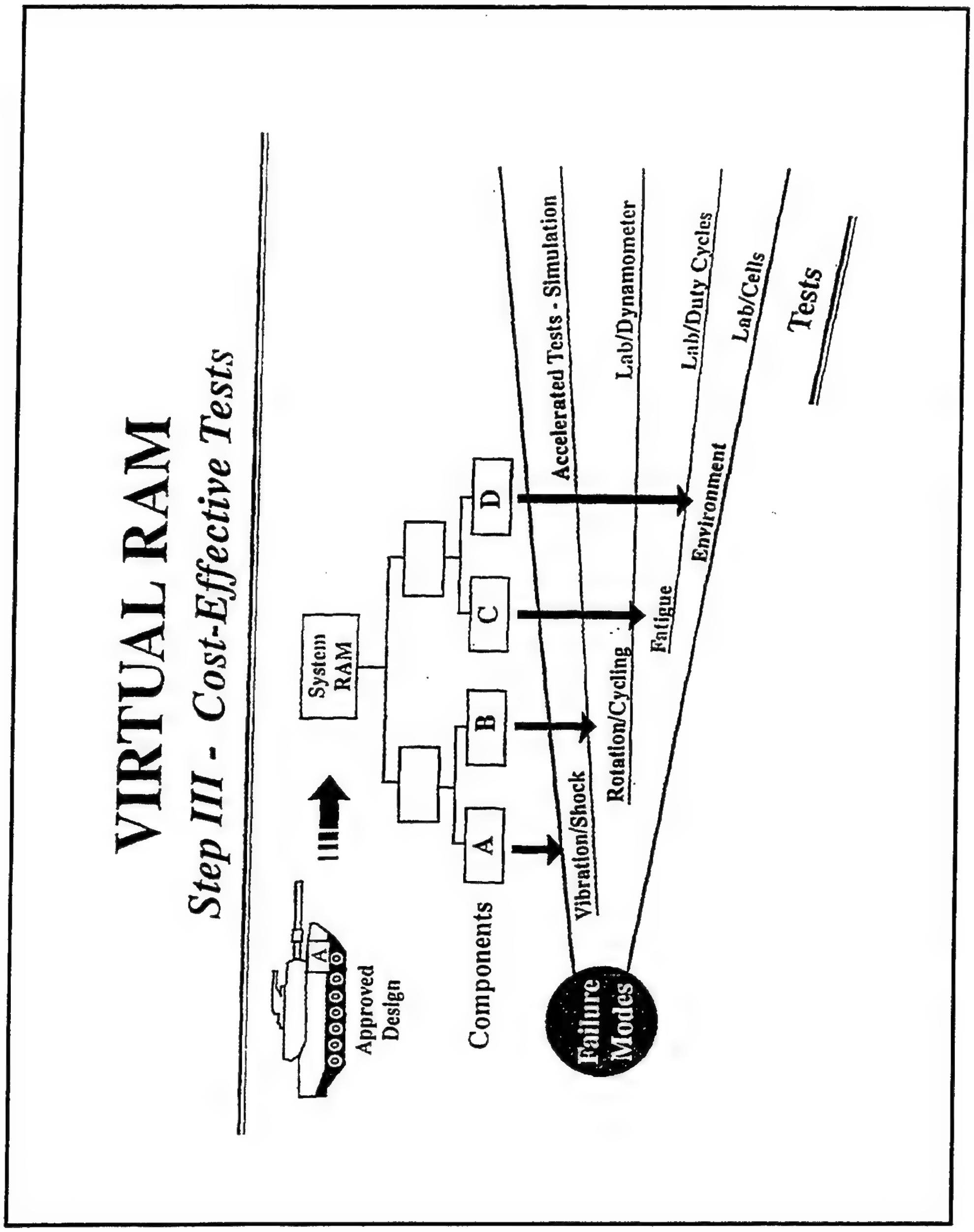
M1A1 Failure Mode Analysis Backup

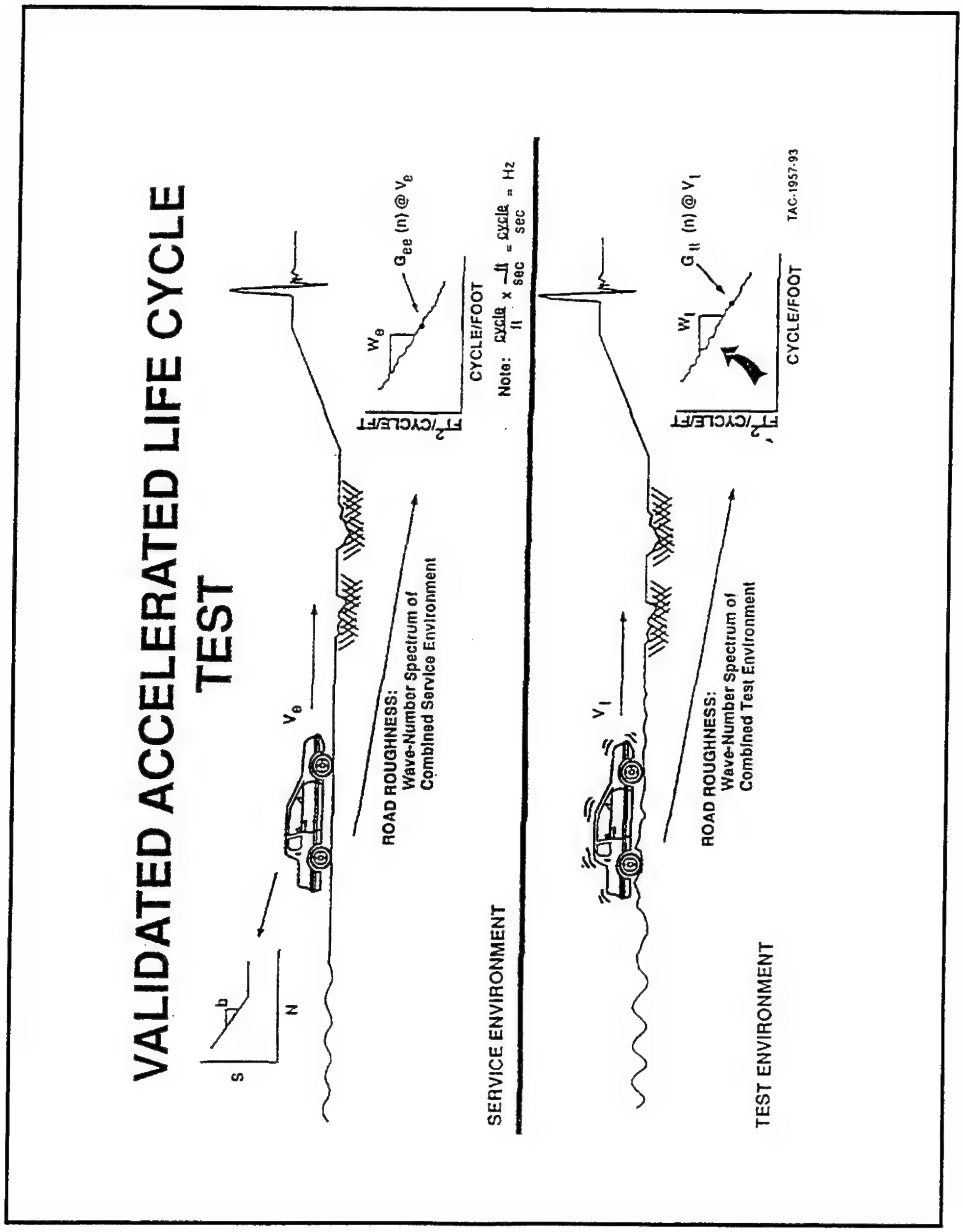
Based on data derived for the M1A1 prediction update)

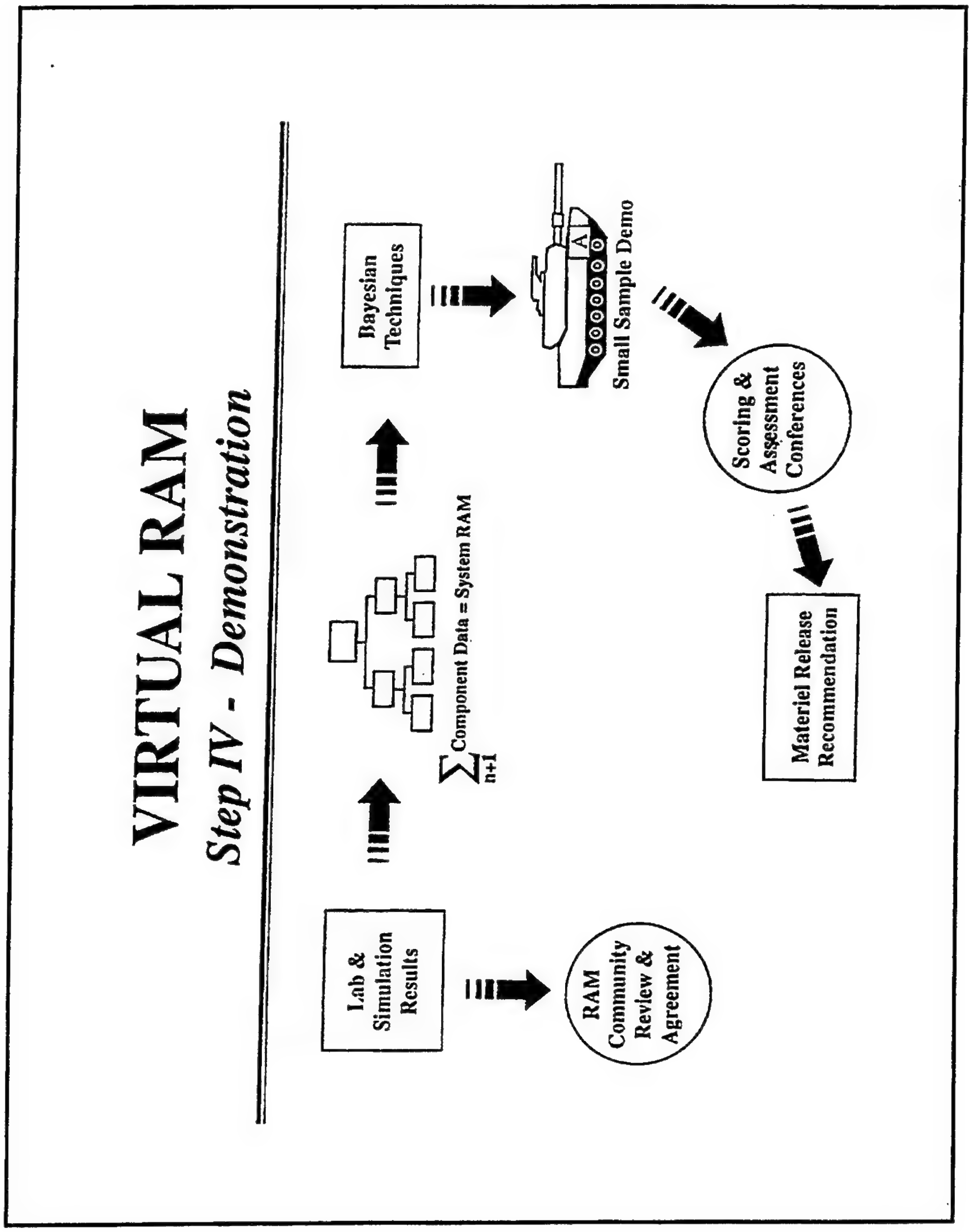
A2A - Torsion bars	Failures	Percent
• Missing/damaged torsion bar covers	8.0	80.0%
• Missing/damaged grease fittings	1.0	10.0%
• Fractured/damaged torsion bar	1.0	10.0%
Totals:	10.0	100.0%

A2B - Shock absorber assembly	Failures	Percent
• Leaking shock	68.4	86.1%
• Loose/missing housing bolts	6.0	7.6%
• Inoperative shock	2.0	2.7%
• Worn/missing packing on shock plugs	1.0	1.2%
• Improperly machined housing	1.0	1.2%
• Cracked/leaking/damaged sight glass	1.0	1.2%
Totals:	79.4	100.0%

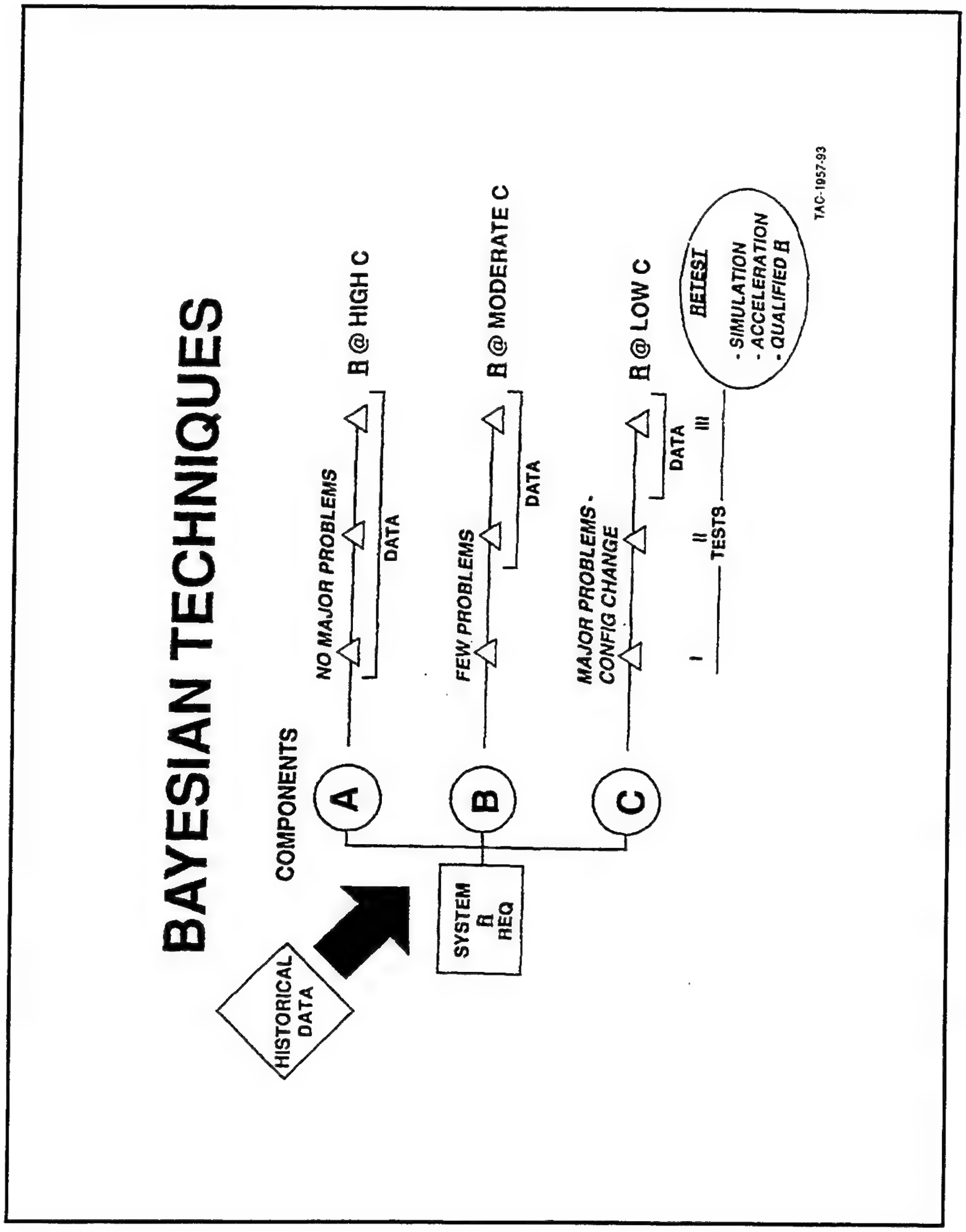
A2C - Roadwheel arm & hub assemblies	Failures	Percent
• Worn/chunked roadwheels	98.8	53.8%
• Cracked/damaged roadwheel	15.0	8.1%
• Cracked/damaged roadarm/roadwheel bolts	12.0	6.5%
• Loose/missing roadarm/roadwheel bolts	9.0	4.8%
• Contaminated roadarm	8.0	4.3%
• Cracked/leaking/damaged roadarm hubcap	8.0	4.3%
• Loose/missing wearplate bolts	7.0	3.8%
• Leaking dust plug	6.0	3.2%
• Leaking roadarm/hub seal	5.0	2.7%
• Worn/cracked wearplate	4.0	2.2%
• Other	12.0	6.3%
Totals:	184.8	100.0%

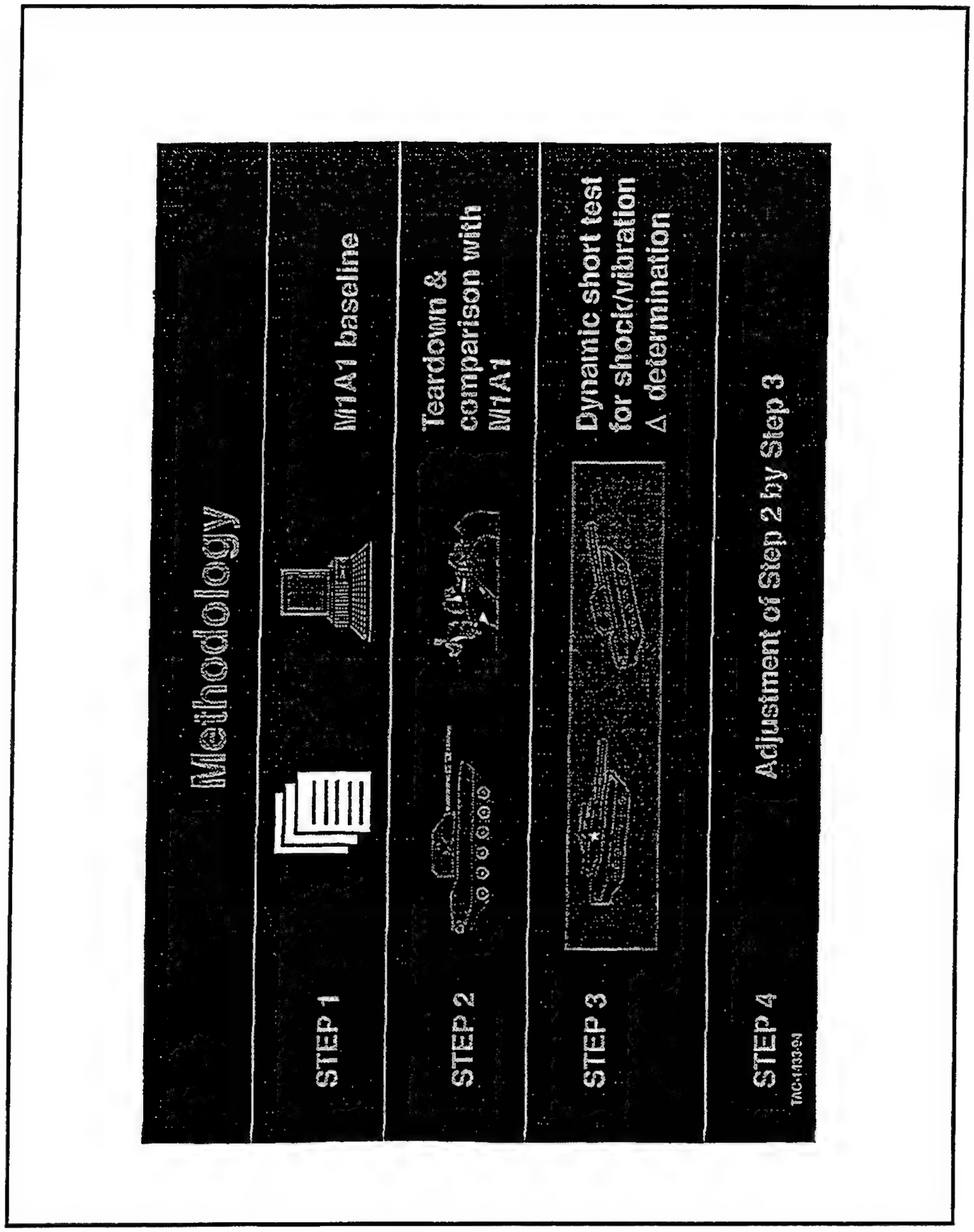

VIRTUAL RAM
Step III - Cost-Effective Tests
Approved Design
A
III
System RAM
Components
A
B
C
D
Failure Modes
Vibration/Shock
Rotation/Cycling
Fatigue
Environment
Accelerated Tests - Simulation
Lab/Dynamometer
Lab/Duty Cycles
Lab/Cells
Tests


VALIDATED ACCELERATED LIFE CYCLE TEST
S
b
N
V_e
W_e
G_{ee} (n) @ V_e
FT^2/CYCLE/FT
CYCLE/FOOT
ROAD ROUGHNESS:
Wave-Number Spectrum of
Combined Service Environment
Note: $\frac{cycle}{ft} \times \frac{ft}{sec} = \frac{cycle}{sec} = Hz$
SERVICE ENVIRONMENT
V_t
W_t
G_{tt} (n) @ V_t
FT^2/CYCLE/FT
CYCLE/FOOT
ROAD ROUGHNESS:
Wave-Number Spectrum of
Combined Test Environment
TEST ENVIRONMENT
TAC-1957-93



VIRTUAL RAM
Step IV - Demonstration
Lab & Simulation Results
RAM Community Review & Agreement
Component Data = System RAM
n+1
Bayesian Techniques
A
Small Sample Demo
Scoring & Assessment Conferences
Materiel Release Recommendation


BAYESIAN TECHNIQUES
HISTORICAL DATA
COMPONENTS
SYSTEM R REQ
A
B
C
NO MAJOR PROBLEMS
DATA
R @ HIGH C
FEW PROBLEMS
DATA
R @ MODERATE C
MAJOR PROBLEMS - CONFIG CHANGE
DATA
R @ LOW C
I
II
TESTS
III
RETEST
- SIMULATION
- ACCELERATION
- QUALIFIED R
TAC-1957-93


Methodology
STEP 1
M1A1 baseline
STEP 2
Teardown & comparison with M1A1
STEP 3
Dynamic short test for shock/vibration Δ determination
STEP 4
Adjustment of Step 2 by Step 3

METHODOLOGY MATHEMATICS

$$\text{M1A1 BASELINE}'_{(C)} \times \Delta\%_{\text{T-72 VS. M1A1}} = \text{T-72 VALUE}_{(C)}$$

$$\sum \text{T-72}_{(C)} = \text{T-72}_{(S)}$$

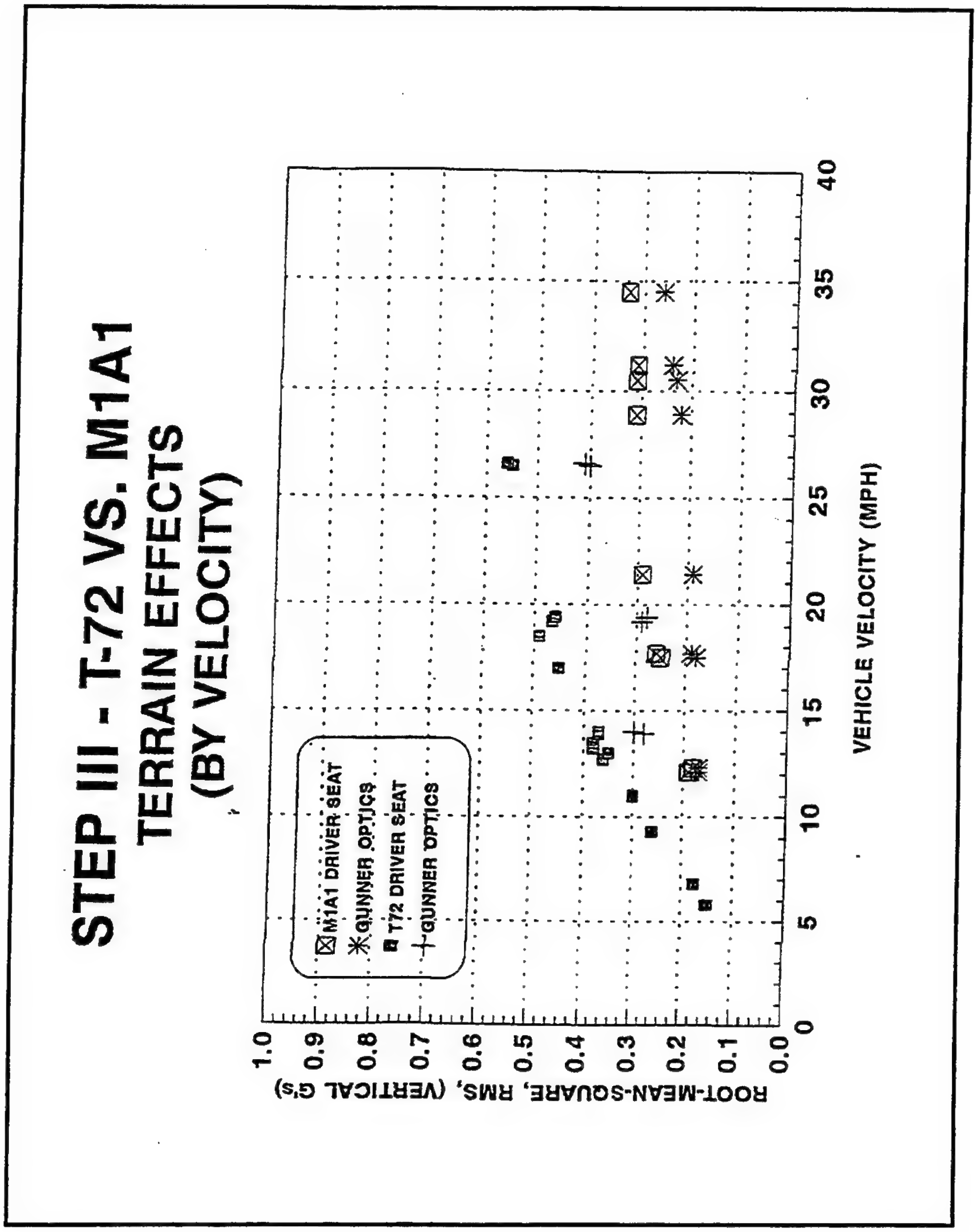
M1A1 VS. T-72 TERRAIN EFFECTS FACTOR = % F

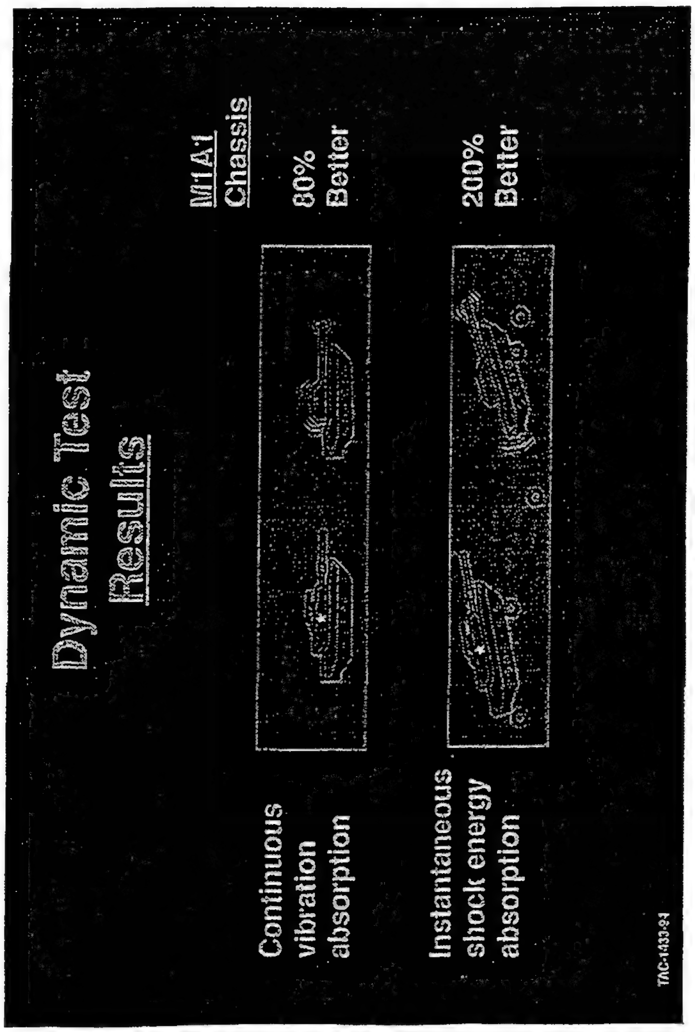
% M1A1 FAILURE MODES AFFECTED BY TERRAIN EFFECTS = % M

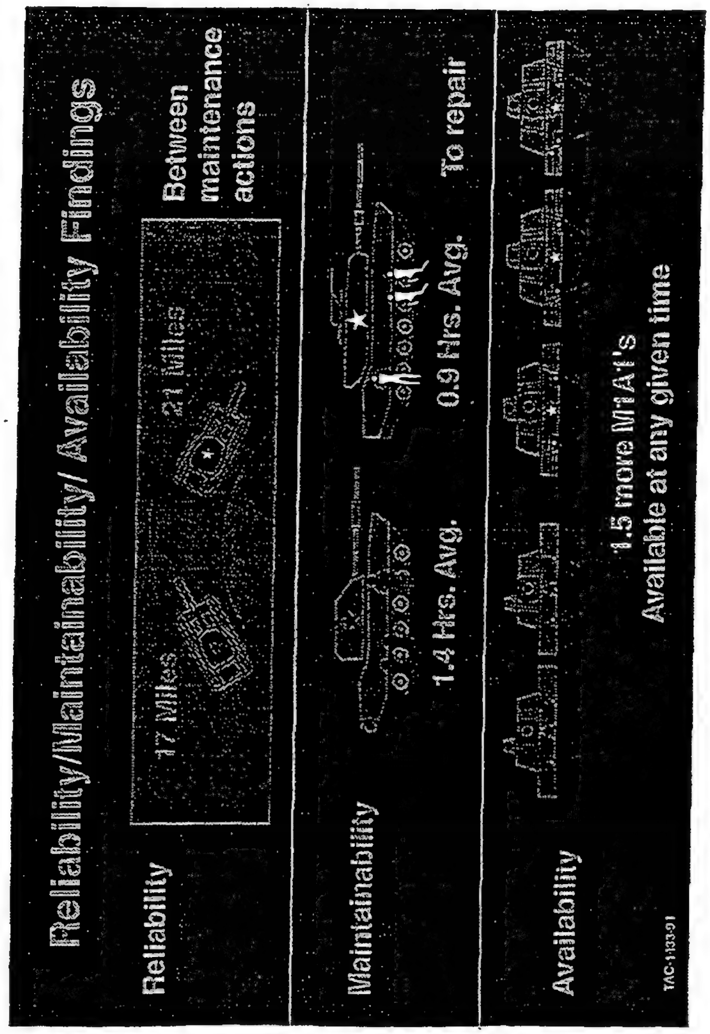
% M X % F = **% EFFECT**

$$\text{T-72}_{(S)} \times \%\ \text{EFFECT} = \text{T-72 R\&M}$$

(C) - COMPONENTS
(S) - SYSTEM


STEP III - T-72 VS. M1A1
TERRAIN EFFECTS
(BY VELOCITY)
M1A1 DRIVER SEAT
GUNNER OPTICS
T72 DRIVER SEAT
GUNNER OPTICS
ROOT-MEAN-SQUARE, RMS, (VERTICAL G's)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
5
10
15
20
25
30
35
40
VEHICLE VELOCITY (MPH)


Dynamic Test Results
M1A1 Chassis
Continuous vibration absorption
80% Better
Instantaneous shock energy absorption
200% Better


Reliability/Maintainability/ Availability Findings
Reliability
17 Miles
21 Miles
Between maintenance actions
Maintainability
1.4 Hrs. Avg.
0.9 Hrs. Avg.
To repair
Availability
1.5 more M1A1's
Available at any given time
TAC-1133-91

704

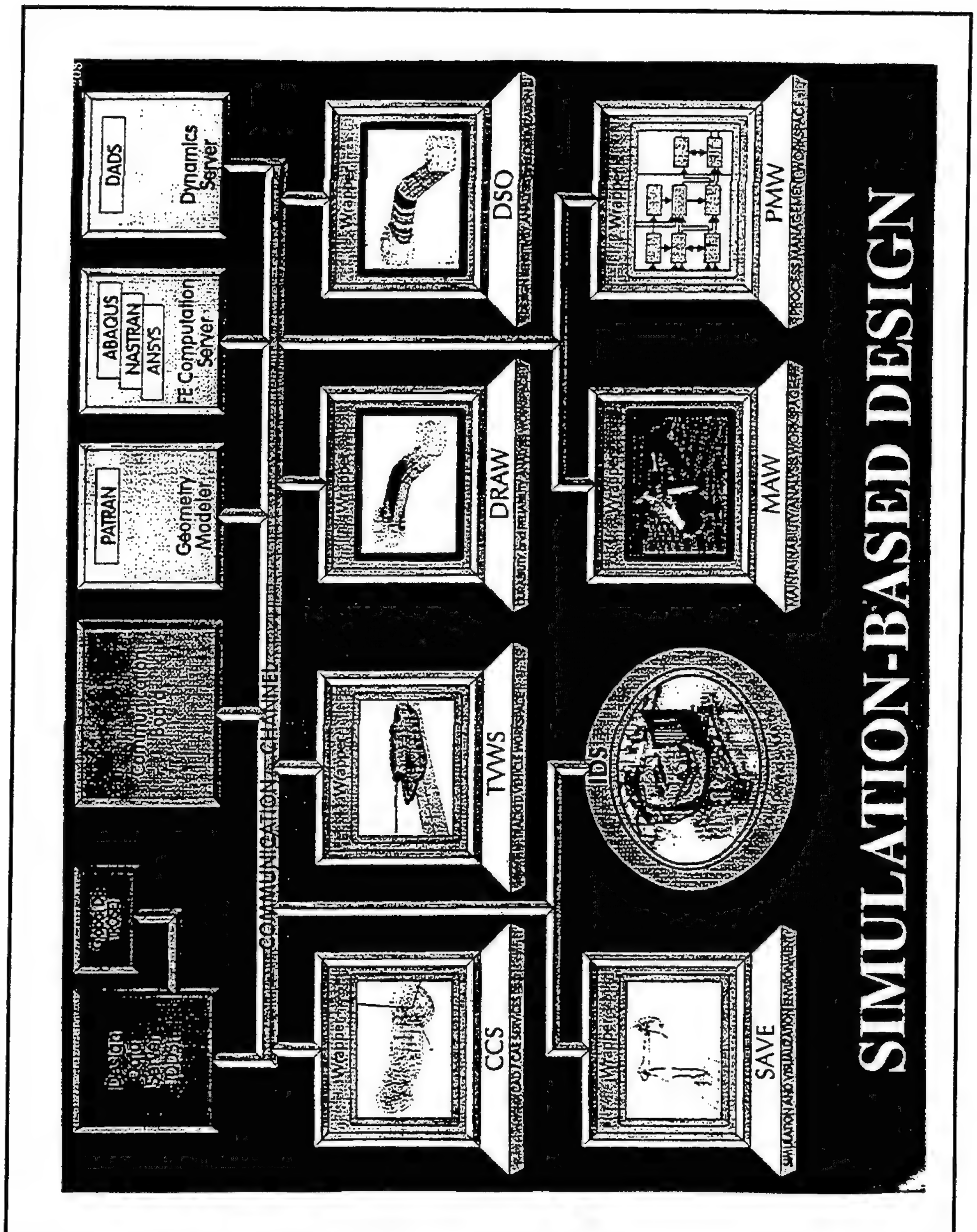
ENABLING TECHNOLOGIES FOR DRIVING SIMULATION AND VIRTUAL PROVING GROUND APPLICATIONS

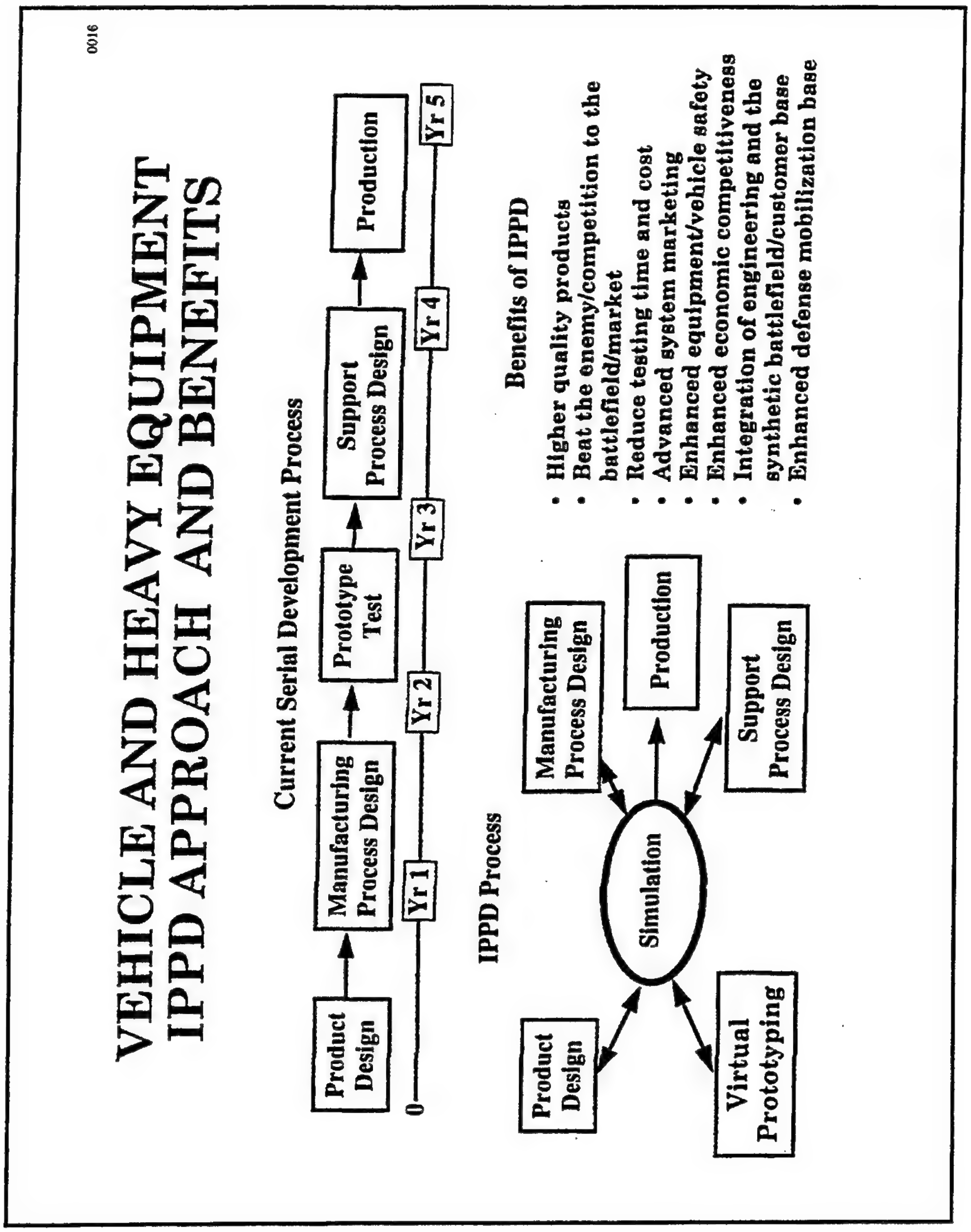
Ed Haug
Center for Computer Aided Design
and
Department of Mechanical Engineering
The University of Iowa

ARPA NSF I/UCRC

Overview

- VPS environment (SBD)
- Progress to Date
  - 4 examples
- Driving Simulation Tools
  - IDS, NADS
- Future Work
  - HMMWV VPG link to VPS
  - M1 VPG Demo


SIMULATION-BASED DESIGN
PATRAN
Geometry Modeler
ABAQUS
NASTRAN
ANSYS
FE Computation Server
DADS
Dynamics Server
COMMUNICATION CHANNEL
Wrapper
CCS
TVWS
DRAW
DSO
IDS
SAVE
SIMULATION AND VISUALIZATION ENVIRONMENT
MAW
PMW
PROCESS MANAGEMENT WORKSPACE


0016
VEHICLE AND HEAVY EQUIPMENT
IPPD APPROACH AND BENEFITS
Current Serial Development Process
Product Design
Manufacturing Process Design
Prototype Test
Support Process Design
Production
0
Yr 1
Yr 2
Yr 3
Yr 4
Yr 5
IPPD Process
Product Design
Manufacturing Process Design
Production
Support Process Design
Simulation
Virtual Prototyping
Benefits of IPPD
• Higher quality products
• Beat the enemy/competition to the battlefield/market
• Reduce testing time and cost
• Advanced system marketing
• Enhanced equipment/vehicle safety
• Enhanced economic competitiveness
• Integration of engineering and the synthetic battlefield/customer base
• Enhanced defense mobilization base

Some Progress to Date

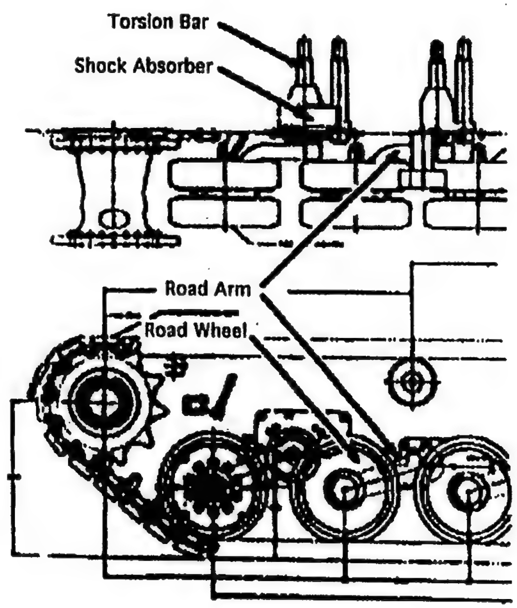
- DICE Tracked Vehicle Concurrent Engineering (DARPA)
- HMMWV Lower Control Arm (NSF)
- Ford Taurus Design Optimization Application
- ARPA IPPD Simulation for Acquisition (HMMWV VPG Simulation)

DICE-TVWS Example

- ARPA supported formation of Testbed to examine VPS capabilities
- 3 companies (FMC, GDLS, BMY) and TACOM
- Realistic Tracked Vehicle example used to help guide development

0006

TRACKED VEHICLE GENERIC APPLICATION: ROAD ARM CAD MODELING AND DYNAMIC ANALYSIS



- Road Arm Associated Suspension Subsystem Part; Geometries and Mass Property Data Defined Utilizing Unigraphics CAD System
- TVWS Utilized to Define Rigid Body Model of Suspension Subsystem; Derived From Unigraphics CAD Geometry and Mass Property Data
- DADS Dynamic Analysis Performed in TVWS; Establishes Load History for Subsequent CE Tool Analyses

DICE Example

- DSO used to initiate structural analysis using load histories from TVWS
- DRAW computed dynamic stress histories for high stress areas
- DRAW predicted fatigue life
  - rainflow technique and NASA/FLAGRO

DICE Example

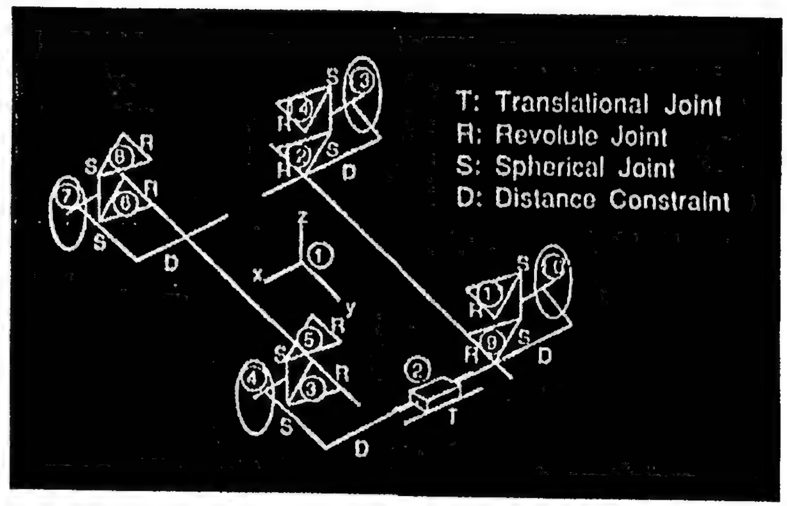
- DSO used to produce
  - design sensitivities
  - color sensitivity plots
  - propose new design
- DSLP done on new design
- new design had significantly longer life (10^7-10^{10})

HMMWV Lower Control Arm

- Validation of VPS
- Address actual design problem that occurred with lower control arm
- SAVE used to launch DADs offline simulation of HMMWV over extreme terrain under extreme loading conditions

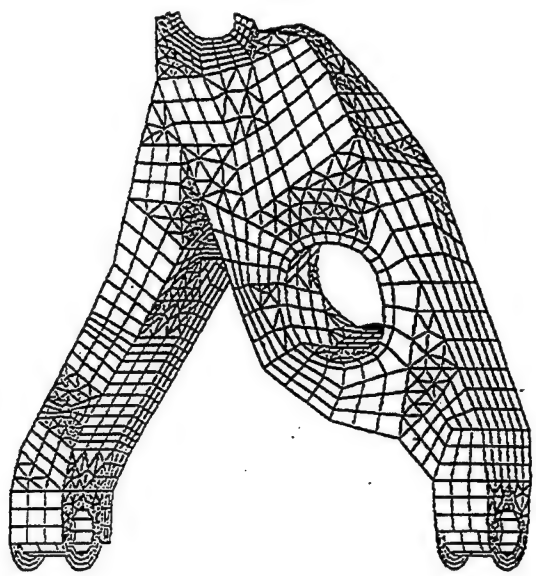
0078

HMMWV MODEL FOR DYNAMIC SIMULATION

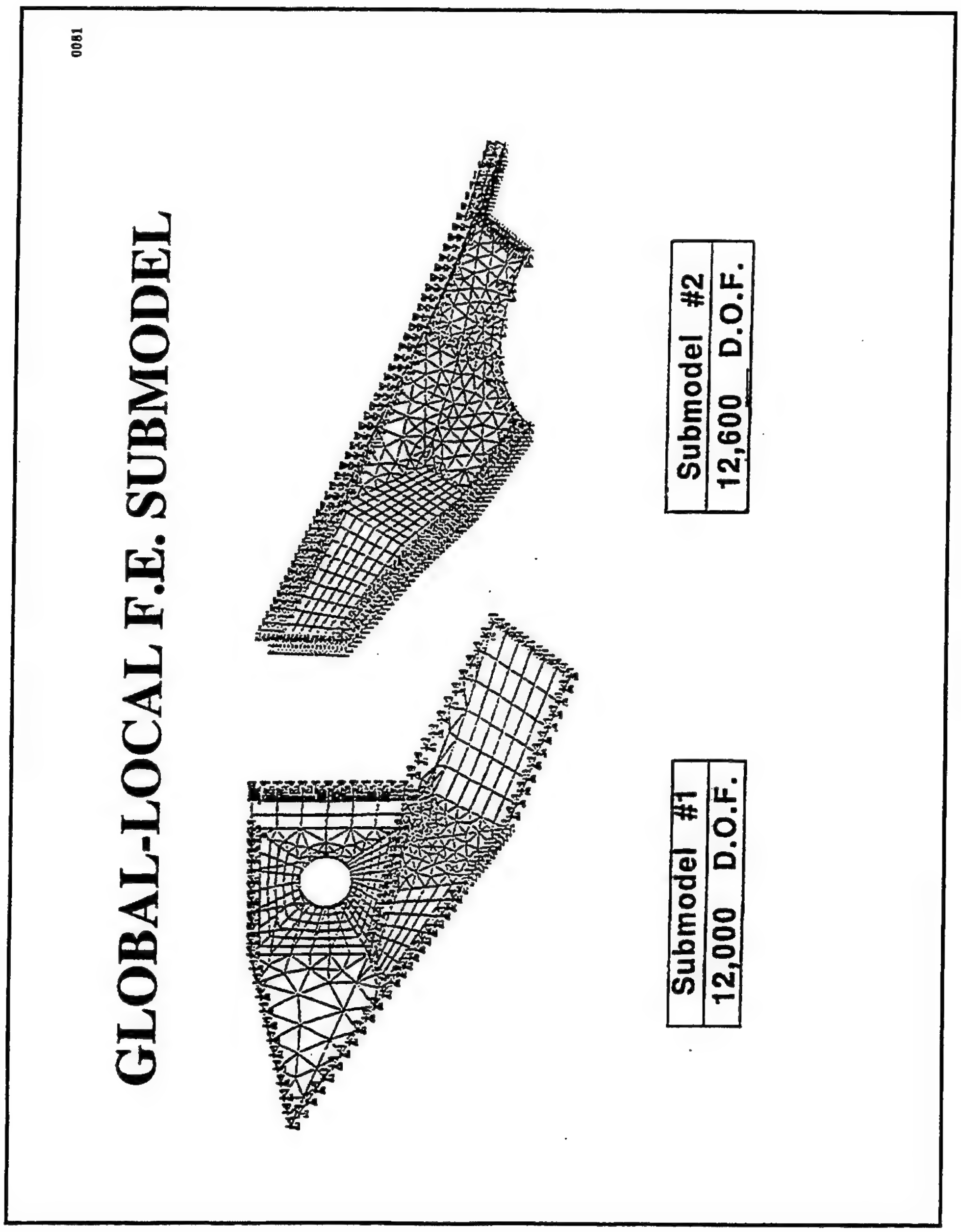


FINITE ELEMENT MODEL OF HMMWV LOWER CONTROL ARM

0080



3500 Shell Elements	
56 Solid Elements	
96 Beam Elements	
16,000 D.O.F.	


0081
GLOBAL-LOCAL F.E. SUBMODEL
Submodel #1
12,000 D.O.F.
Submodel #2
12,600 D.O.F.

008

COMPARISONS OF ANALYSIS AND EXPERIMENT

	Analysis	Experiment	Difference
Stresses	Finite Element Analysis	Strain Gage	Max. 5.8% Min. 1%
Fatigue Life (Number of Blocks)	813	1218 1043 850 Average 1037	21.6%

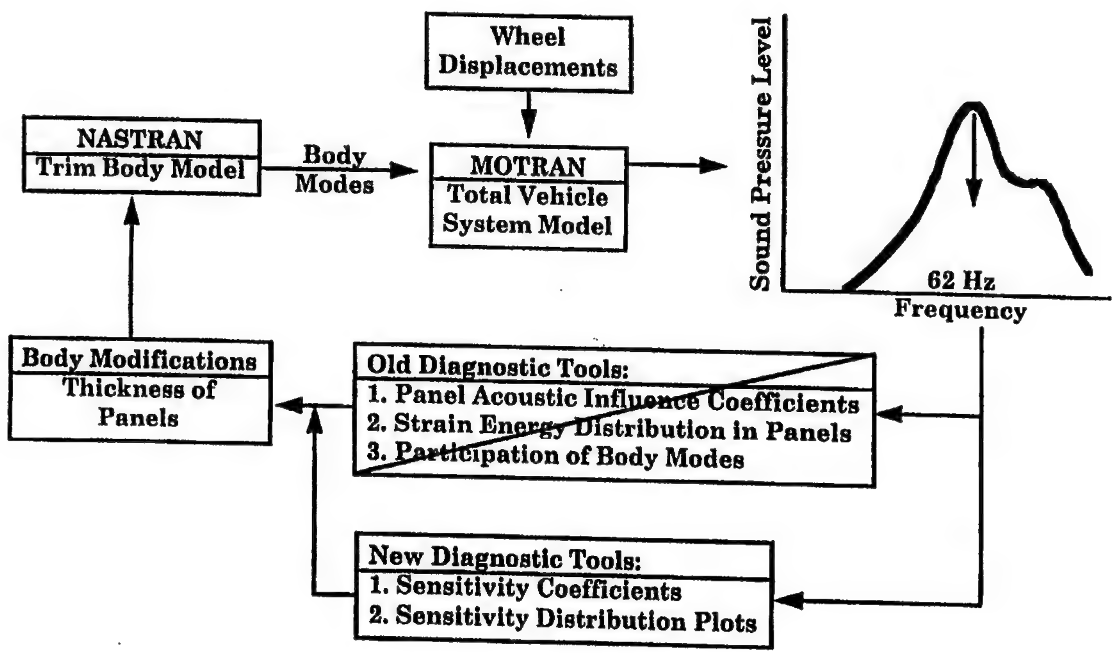
$$\text{Difference} = \left| \frac{\text{Experiment} - \text{Analysis}}{\text{Experiment}} \right|$$

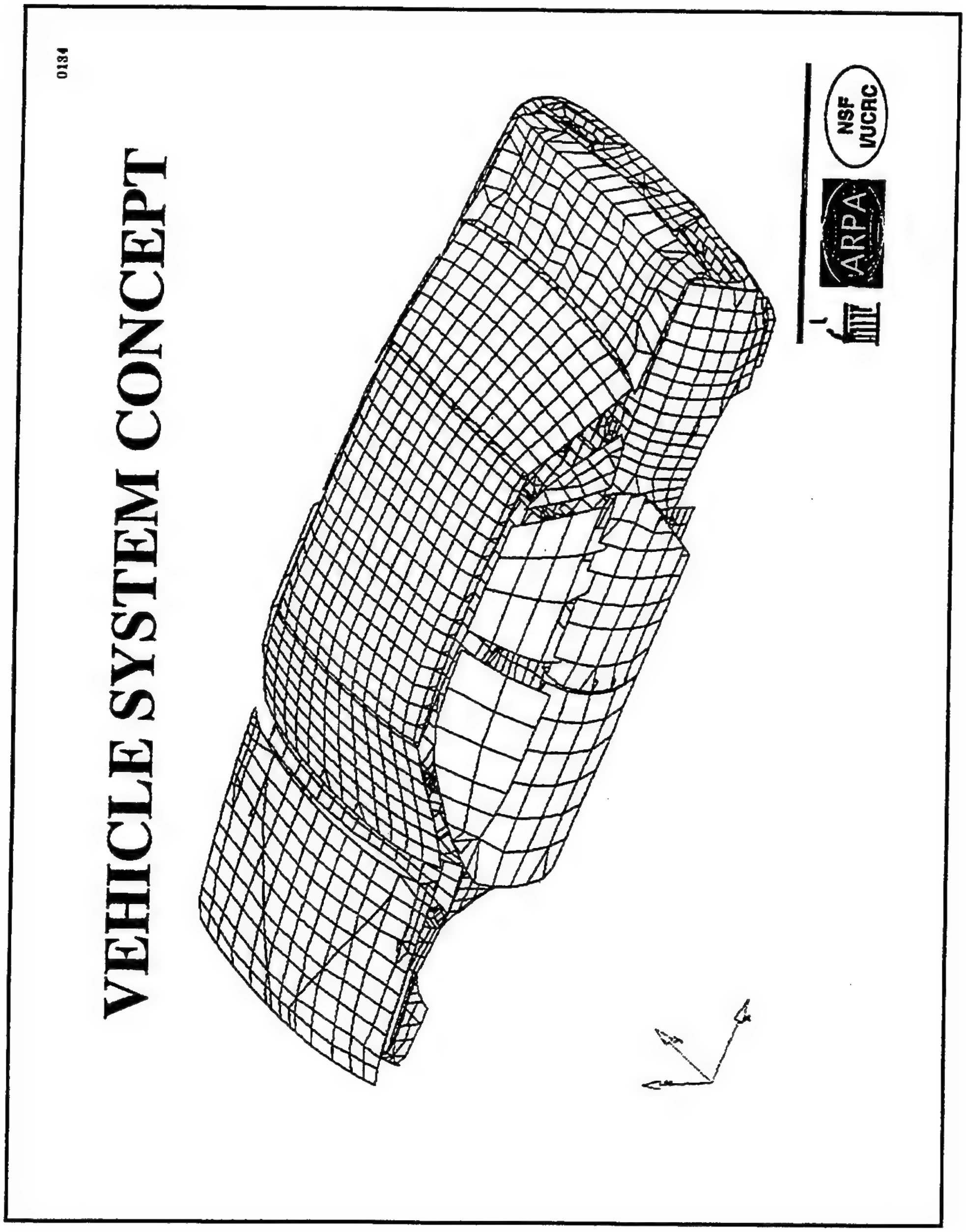
1 Block = 1 Load Time History

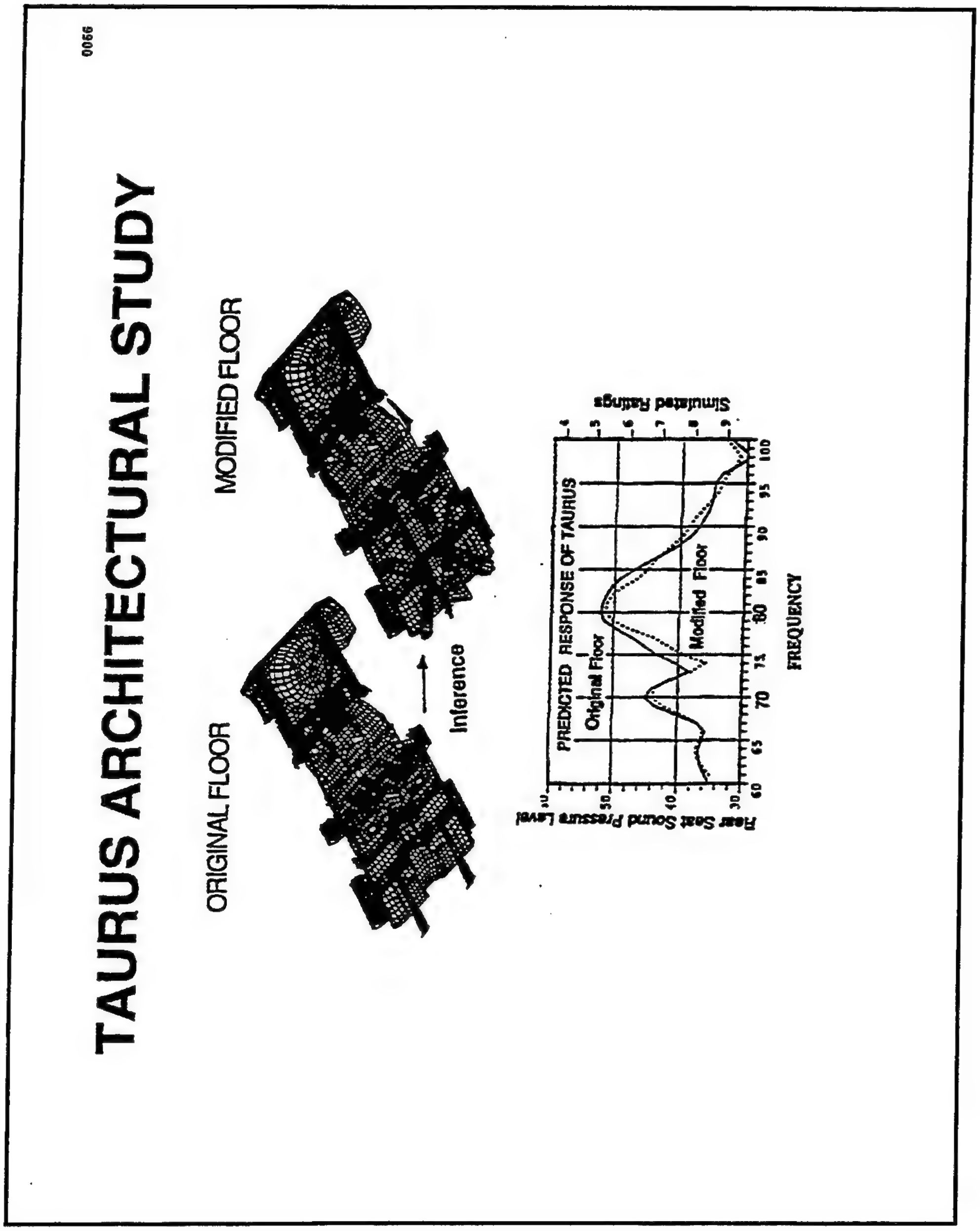
Ford Noise, Vibration and Harshness Study

FORD ADOPTS DESIGN METHODOLOGY FOR NOISE, VIBRATION AND HARSHNESS (NVH)

0008




0134
VEHICLE SYSTEM CONCEPT
ARPA
NSF
I/UCRC

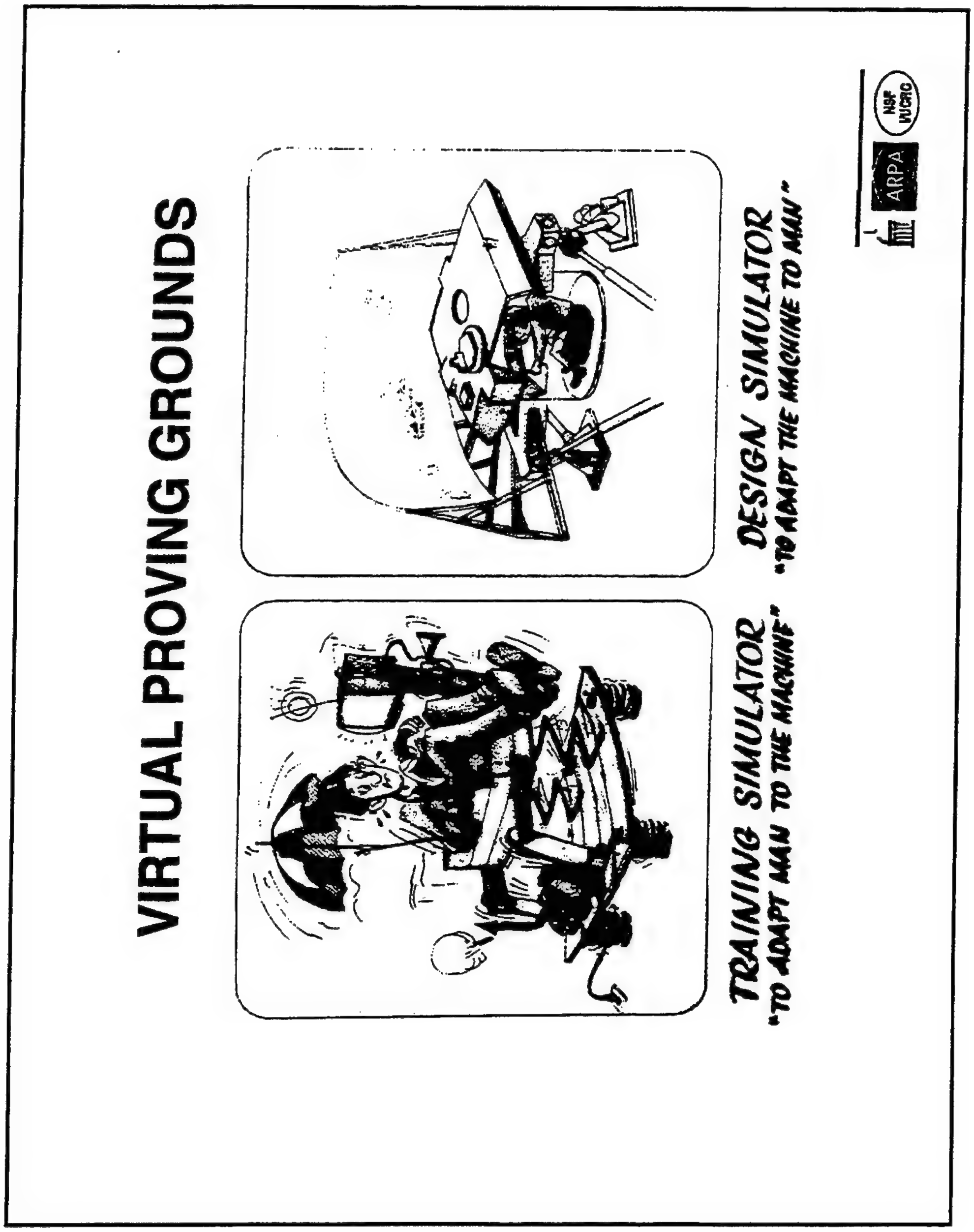


0066
TAURUS ARCHITECTURAL STUDY
ORIGINAL FLOOR
MODIFIED FLOOR
Inference
PREDICTED RESPONSE OF TAURUS
Original Floor
Modified Floor
Rear Seat Sound Pressure Level
Simulated Ratings
FREQUENCY

0026

IMPACT OF TAURUS/ SABLE REDESIGN

- Reduction in Design Time; Six Months to One Week
- Twelve Pound Per Car Reduction in Weight; $18 Million Per Year Saving
  - No reduction in NVH rating
  - No reduction in durability/safety
  - Uses current manufacturing process
- Springboard to Application Throughout Ford


VIRTUAL PROVING GROUNDS
TRAINING SIMULATOR
"TO ADAPT MAN TO THE MACHINE"
DESIGN SIMULATOR
"TO ADAPT THE MACHINE TO MAN"
ARPA

ENABLING TECHNOLOGIES FOR DRIVING SIMULATION AND VIRTUAL PROVING GROUND APPLICATIONS

Ed Haug
Center for Computer Aided Design
and
Department of Mechanical Engineering
The University of Iowa

Overview

- VPS environment (SBD)
- Progress to Date
  - 4 examples
- Driving Simulation Tools
  - IDS, NADS
- Future Work
  - HMMWV VPG link to VPS
  - M1 VPG Demo

NRMM IN THE ACQUISITION PROCESS

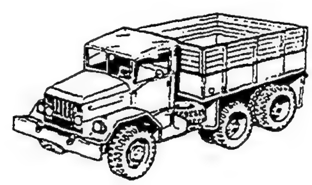
- FIRST USED IN HEMTT PROCUREMENT - 1980
- USED:
  - TO DEVELOP THE PERFORMANCE SYSTEM SPECIFICATIONS
  - TO ASSESS OFFEROR'S PROPOSED SYSTEMS
- DISSEMINATED TO SERIOUS OFFEROR'S RESPONDING TO AN RFP.
- AS PART OF AN RFP PACKAGE:
  - SOW STATES USE OF NRMM IN ASSESSING PERFORMACE AFTER AWARD.
  - ATPD CONTAINS SPECIFICATIONS IN NRMM TERMS.
    - GLOBAL SPECIFICATIONS
    - SUB-SYSTEM PERFORMANCE
  - NRMM VEHICLE DATA SHEETS SUBMITTED WITH PROPOSAL.
  - SSP STATES USE OF NRMM IN SSEB.

LAND TECHNOLOGY COORDINATING PAPER
OFFICE OF THE SECRETARY OF DEFENSE
1974

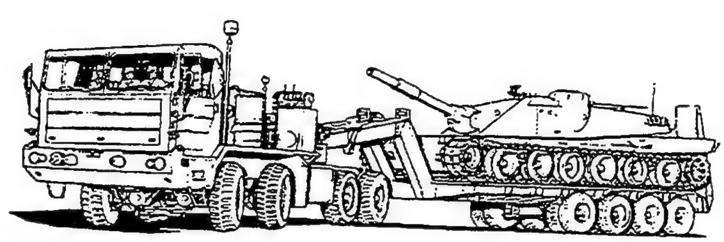
MOBILITY DOCTRINE:

- THREE LEVELS OF MOBILITY PROMULGATED IN THE ARMY "WHEELS" STUDY, 1974.
- 1. TACTICAL HIGH MOBILITY. The highest level of mobility designating the requirement for extensive cross-country maneuverability characteristic of operations in the ground gaining and fire support environment.
- 2. TACTICAL STANDARD MOBILITY. The second highest lelev of mobility designating the requirement for occasional cross-country movement.
- 3. TACTICAL SUPPORT MOBILITY. A level of mobility designating the requirement for infrequent off-road operations over selected terrain with the preponderance of movement on primary and secondary roads.

XM723 MECHANIZED INFANTRY COMBAT VEHICLE
(Example of Tactical High Mobility)



TACTICAL TRUCK 2-½ TON M35
(Example of Tactical Standard Mobility)



HEAVY EQUIPMENT TRANSPORTER M746/7
(Example of Tactical Support Vehicle)

Figure 3–1. Mobility Doctrine

QUANTIFICATION OF "WHEELS" STUDY DEFINITIONS OF TACTICAL MOBILITY

	Operating Distance		Severity of Operation	
			Off-Road	On-Road
MOBILITY LEVEL	Off-Road Percent	On-Road Percent	Percent of Terrain Challenged	Percent of Trails Included
TACTICAL HIGH	50	50	90	100
TACTICAL STANDARD	15	85	80	100
TACTICAL SUPPORT	5	95	50	50

QUANTIFICATION OF "WHEELS" STUDY DEFINITIONS OF TACTICAL MOBILITY

MISSION PROFILE - PERCENT DISTANCE

WESTERN EUROPE

MOBILITY LEVEL	Primary Roads	Secondary Roads	Trails	Cross-Country
TACTICAL HIGH	10%	30%	10%	50%
TACTICAL STANDARD	20%	50%	15%	15%
TACTICAL SUPPORT	30%	55%	10%	5%

MIDDLE EAST

MOBILITY LEVEL	Primary Roads	Secondary Roads	Trails	Cross-Country
TACTICAL HIGH	5%	20%	25%	50%
TACTICAL STANDARD	15%	35%	35%	15%
TACTICAL SUPPORT	20%	40%	35%	5%

QUANTIFICATION OF "WHEELS" STUDY DEFINITIONS OF TACTICAL MOBILITY

MOBILITY RATING SPEEDS - WESTERN EUROPE

MOBILITY LEVEL	Severity of Operation: Off-Road — Percent of Terrain Challenged	Severity of Operation: On-Road — Percent of Trails Included	Average Speed - V_X Over Percent of Terrain Type Challenged: Primary Roads	Secondary Roads	Trails	Cross Country
TACTICAL HIGH	90	100	V_{100}	V_{100}	V_{100}	V_{90}
TACTICAL STANDARD	80	100	V_{100}	V_{100}	V_{100}	V_{80}
TACTICAL SUPPORT	50	50	V_{100}	V_{100}	V_{50}	V_{50}

- Mobility Rating Speed - The average speed for the terrain surface types mission profile = $\frac{\text{Distance}}{\text{Time}}$

$$\text{Mobility Rating Speed} = \frac{100\% \text{ of Distance}}{\frac{\%\text{Primary}}{V_X} + \frac{\%\text{Secondary}}{V_X} + \frac{\%\text{Trails}}{V_X} + \frac{\%\text{Cross-Country}}{V_X} + \%\text{TP Off-Road}}$$

QUANTIFICATION OF "WHEELS" STUDY DEFINITIONS OF TACTICAL MOBILITY

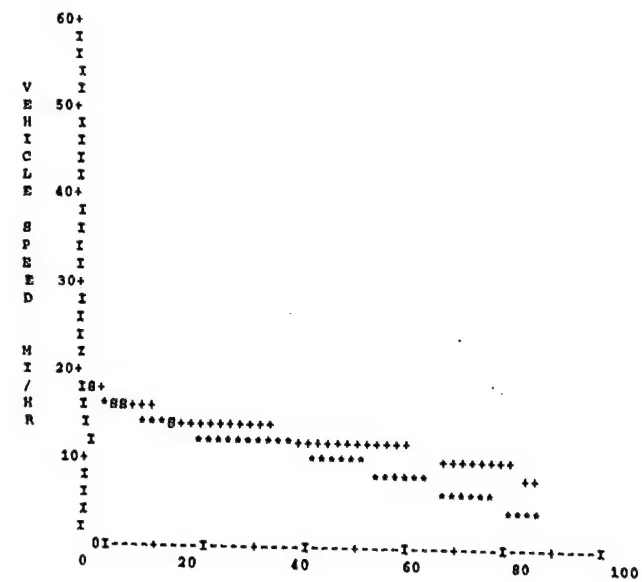
MOBILITY RATING SPEEDS - MIDDLE EAST

	Severity of Operation		Average Speed - V_X Over Percent of Terrain Type Challenged			
	Off-Road	On-Road				
MOBILITY LEVEL	Percent of Terrain Challenged	Percent of Trails Included	Primary Roads	Secondary Roads	Trails	Cross Country
TACTICAL HIGH	90	100	V_{100}	V_{100}	V_{100}	V_{90}
TACTICAL STANDARD	80	100	V_{100}	V_{100}	V_{100}	V_{80}
TACTICAL SUPPORT	50	50	V_{100}	V_{100}	V_{80}	V_{50}

- Mobility Rating Speed - The average speed for the terrain surface types mission profile = $\frac{\text{Distance}}{\text{Time}}$

$$\text{Mobility Rating Speed} = \frac{100\% \text{ of Distance}}{\frac{\%\text{Primary}}{V_X} + \frac{\%\text{Secondary}}{V_X} + \frac{\%\text{Trails}}{V_X} + \frac{\%\text{Cross-Country}}{V_X} + \%\text{TP Off-Road}}$$

THE VEHICLE IS ICBT - HDSS/HDSS - THE GEOGRAPHIC AREA IS EFOSS QUAD L5322, THE SEASON IS DRY



ACCUMULATED PERCENT AREA

	X=0	2	4	6	8
	18.5	17.6	16.3	15.5	15.0
1X	14.6	14.0	13.4	13.2	12.9
2X	12.6	12.4	12.2	12.0	11.8
3X	11.7	11.6	11.4	11.1	10.9
4X	10.7	10.4	10.1	9.7	9.3
5X	8.9	8.5	8.1	7.7	7.3
6X	7.0	6.8	6.6	6.2	6.0
7X	5.7	5.3	4.9	4.2	3.6
8X	3.3	0.0	0.0	0.0	0.0
9X	0.0	0.0	0.0	0.0	0.0
10X	0.0				

SPEED IN UNIT

ACCUMULATED PERCENT AREA

	X=0	2	4	6	8
	18.5	18.1	17.3	16.6	16.3
1X	15.9	15.6	15.2	15.0	14.6
2X	14.5	14.2	14.1	13.9	13.7
3X	13.6	13.4	13.3	13.1	13.0
4X	12.9	12.7	12.6	12.4	12.3
5X	12.1	11.9	11.7	11.5	11.3
6X	11.1	10.9	10.7	10.4	10.2
7X	10.0	9.8	9.5	9.2	8.9
8X	8.6	0.0	0.0	0.0	0.0
9X	0.0	0.0	0.0	0.0	0.0
10X	0.0				

AVERAGE SPEED

THE NOGO PERCENT OF AREA IS-19.22.

MOBILITY SYSTEM PERFORMANCE SPECIFICATIONS
GLOBAL PERFORMANCE

3.x.x.x. **Mobility.** The vehicle at GVW shall be capable of operating over primary and secondary roads, trails and cross-country under varied environmental conditions specified IAW the Tactical Standard Level of Mobility. The mobility characteristics shall equal or exceed those quantified by the **NATO Reference Mobility Model (NRMM)** version 2.5.7, in the following paragraphs.

3.x.x.x.1 Maximum Percent NO-GO

	Germany			Central America		Southwest Asia	
	Lauterbach			Honduras		Middle East	
Tactical Standard	Dry	Wet	Snow	Dry	Wet	Dry	Sand
Truck/prime mover	12.0	18.0	18.0	9.0	15.0	10.0	18.0

3.x.x.x.2 Minimum Mobility Rating Speeds (MRS) - MPH

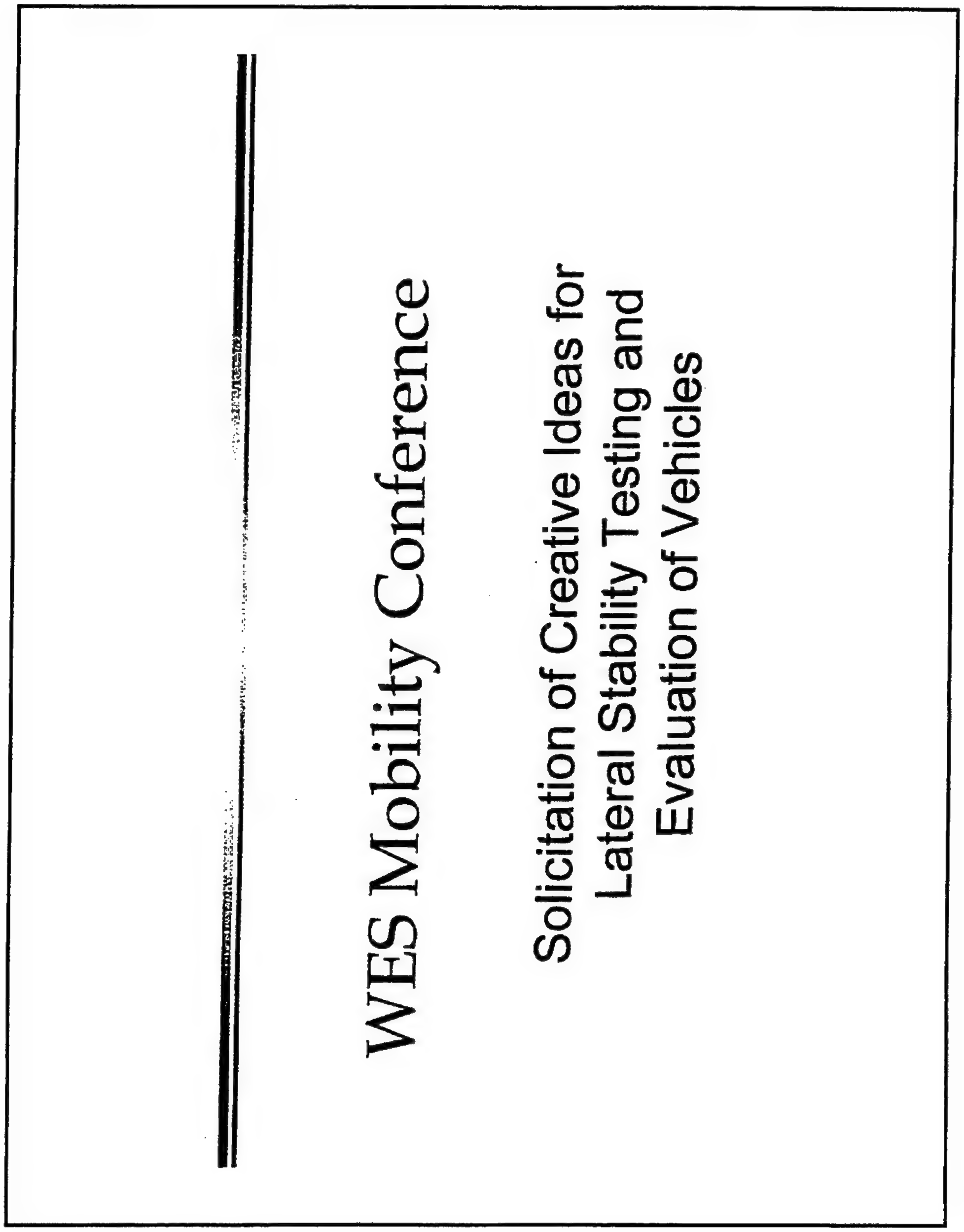
	Germany			Central America		Southwest Asia	
	Lauterbach			Honduras		Middle East	
Tactical Standard	Dry	Wet	Snow	Dry	Wet	Dry	Sand
Truck/prime mover	18.0	16.0	16.0	20.0	17.0	20.0	10.0

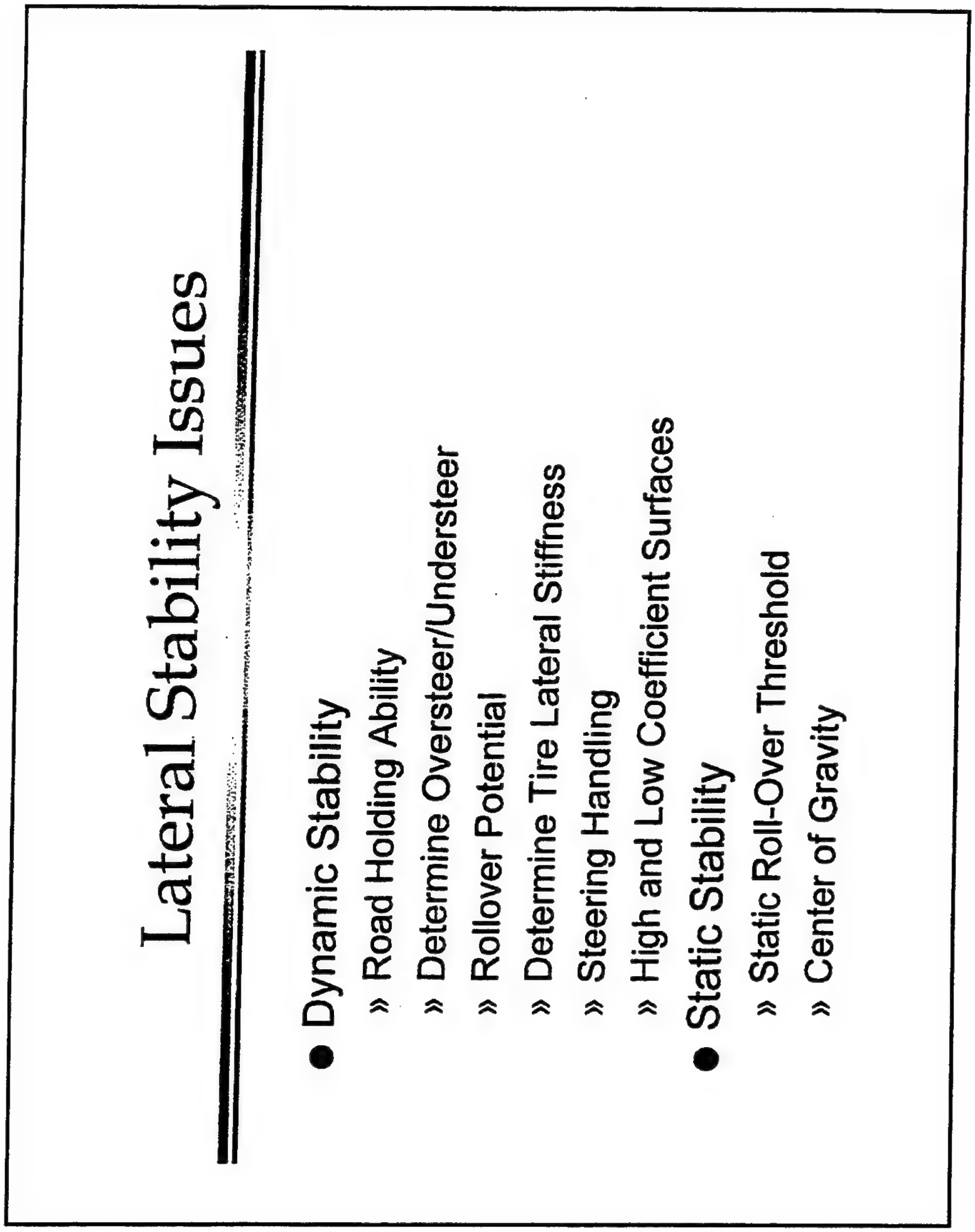
MOBILITY SYSTEM PERFORMANCE SPECIFICATIONS
SUBSYSTEM PERFORMANCE

3.x.x.y **Vehicle Cone Index.** The vehicle at GVW single pass VCI_1 (fine grained) shall have a value no greater than 25 (lowered desired) at the cross-country inflation pressure or which shall permit speeds up to 40 mph for continuous operation on roads, trails and cross-country; a value no greater than 23 at the tire inflation pressure for snow/mud/sand, CTIS equipped, or which will permit speeds up to 12 mph; a value no greater than 21 (lowered desired), CTIS equipped, for emergency operation at speeds not to exceed 5 mph. The calculated VCI_1 (fine grained) shall employ the deflection ratio effect algorithms as defined in NRMM II.

3.x.x.z. **Ride Quality.** The vehicle at GVW shall attain no more than 6 watts average vertical absorbed power at the driver's station (seat base) while negotiating a 0.7 in. (1.8 cm) RMS course at speeds up to 30 mph (48 kph), a 1.0 in (2.5 cm) RMS course at speeds up to 22 mph (43 kph) and 1.5 in. (3.8 cm) RMS course at speeds up to 15 mph (32 kph), with tires at the normal cross-country inflation pressure. The vehicle at GVW shall attain no more than 2.5g vertical acceleration at the driver's station while negotiating half-round obstacles of 10 in. (25 cm) height at speeds up to 15 mph (32 kph) and a half-round obstacle of 12 in. (30 cm) height at speeds up to 7 mph (16 kph) with tires at the normal cross-country inflation pressure.

3.x.x.yy **Vertical Step.** The vehicle at GVW shall be capable of negotiating an 24 inch vertical step forward and backward without sustaining damage to any part of the vehicle.


WES Mobility Conference
Solicitation of Creative Ideas for
Lateral Stability Testing and
Evaluation of Vehicles


Lateral Stability Issues
Dynamic Stability
» Road Holding Ability
» Determine Oversteer/Understeer
» Rollover Potential
» Determine Tire Lateral Stiffness
» Steering Handling
» High and Low Coefficient Surfaces
Static Stability
» Static Roll-Over Threshold
» Center of Gravity

Static Roll Threshold

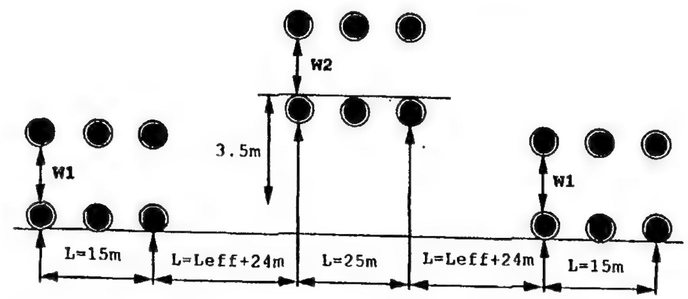
- Establish Static Roll Threshold of the Vehicle at Curb Weight, and at Payload Configurations Established During the Payload Evaluation
- The Vehicle is Instrumented to Determine the Attitude of the Vehicle in Relation to the Tilt Table
- Calculate Estimated Maximum Vehicle Speed for the Constant Radius Turn Evaluation

Static Versus Dynamic Roll Threshold

- Actual Test Result Example
  - » Tilt Table Angle = 32.8 Degrees
  - » Calculated Lateral Acceleration = 0.64 g
  - » Calculated Test Speed = 44 Mph
  - » Actual Test Speed At Wheel Lift = 41 mph

Obstacle Avoidance (Lane Change) Maneuvers

The Obstacle Avoidance Test Course Is Established in Accordance With ISO 3888 As Indicated Below. The Dimensions for the Distance Between the Gates May Be Reduced If a Maximum Vehicle Operating Speed Limitation Is Reached.



W1 = 1.1 (VW) + 0.25m

W2 = 1.2 (VW) + 0.25m

VW = Vehicle Width

Leff = Overall Length of the Vehicle Measured at 0.5m from the Ground

Change Maneuvers (Continued)

- The Obstacle Avoidance Maneuvers Are Conducted Under the Following Test Conditions:
  - » Maneuvers Are Performed at Increasing Speed Increments Until Potential Vehicle Instability Is Encountered.
  - » Maneuvers Are Performed on High and Low Coefficient Surfaces.
  - » Maneuvers Are Performed With and Without the Trailer (If Applicable).
  - » Maneuvers Are Performed at Various Payload and Tire Inflation Pressures.
  - » Inexperienced Driver Maneuvers Are Performed.

200 Foot Constant Radius Maneuver

- The Constant Radius Maneuver Is Executed Through a 360° Arc of a 200 Foot Radius at a Steady Speed.
- The Maneuvers Are Conducted Under the Following Test Conditions:
  - » Maneuvers Are Performed at Increasing Speed Increments Until Potential Vehicle Instability Is Encountered.
  - » Maneuvers Are Performed on High and Low Coefficient Surfaces.
  - » Maneuvers Are Performed With and Without the Trailer (If Applicable).
  - » Maneuvers Are Performed at Various Payload and Tire Inflation Pressures.

Test Methods

- Vary Speed on a Constant Radius Circle
- Vary Circle Radius As Well As Speed
- Potential: Back Out the Salient Parameters From Creative Modeling of Instrumented Vehicle Driven Over Any Range of Speed and Lateral Curvature
- Vary Speed On Severe Lane Change Course
  - » Course Layout Depends on Length and Width of the Vehicle

Instrumentation for Dynamic Stability Evaluations

- Front Axle Lateral Acceleration
- Rear Axle Lateral Acceleration
- Cab Lateral Acceleration
- Position Transducers on to Measure Steering Angle
- Steering Wheel Input Angle
- Payload Roll Rate
- Rear Frame Roll Rate
- Front Frame Roll Rate (at Cab)
- Shaft Encoder to Measure Vehicle Speed
- Yaw Rate at Center of Frame
- Water Trace System to Determine Off-Tracking

ISO Measurements Recommended

- Lateral Acceleration
  - » Correct for roll and side slip
- Yaw Velocity
  - » Correct for roll
- Forward Velocity
  - » Correct for side slip

ISO (continued)

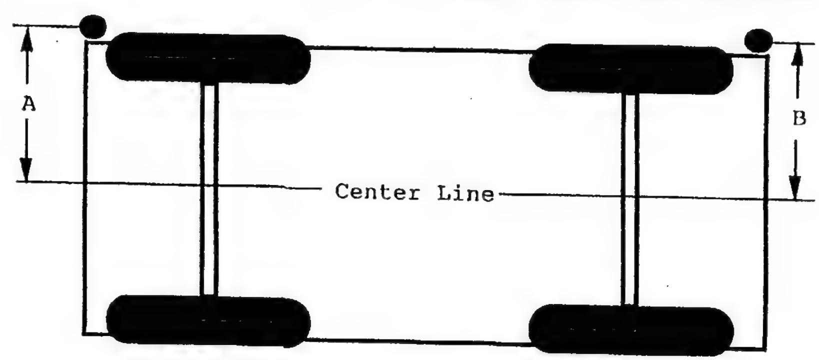
- Sideslip angle
  - » Install transducer per manufacturer recommendation
- Steering wheel torque
- Roll angle
  - » Install transducer per manufacturer recommendations

Most Useful Measurements

- Water Trace Offset for Side-Slip Determination
- Speed
- Steering Angle
- Comparison of Driver Subjective "Comfort" With Measured Vehicle Roll and Yaw Dynamics

Water Trace Layout

- Equip the Vehicles With a Fore and Aft Fluid Trace System and the Distance From the Center of the Vehicle to the Center of the Dispersion Tubes Recorded. After Each Run, Lateral Distances From the Centerline of the Test Track to Each of the Traces Are Recorded at Increments Through the Entire Maneuver.

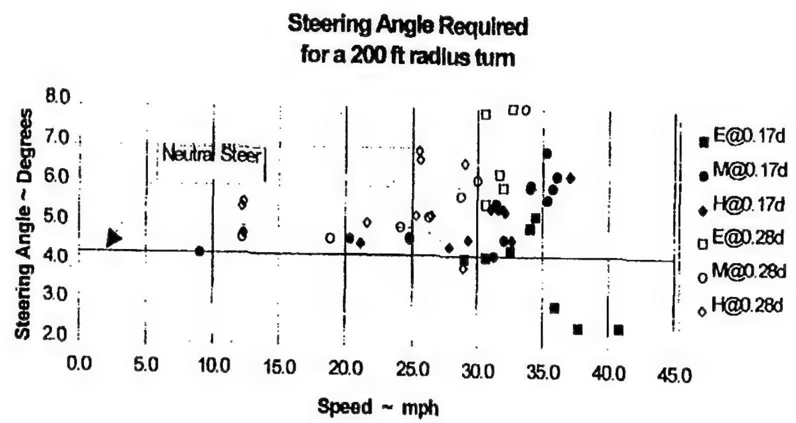


Distance from Center of Vehicle
to Center of Dispersion Tube
A = ______ B = ______

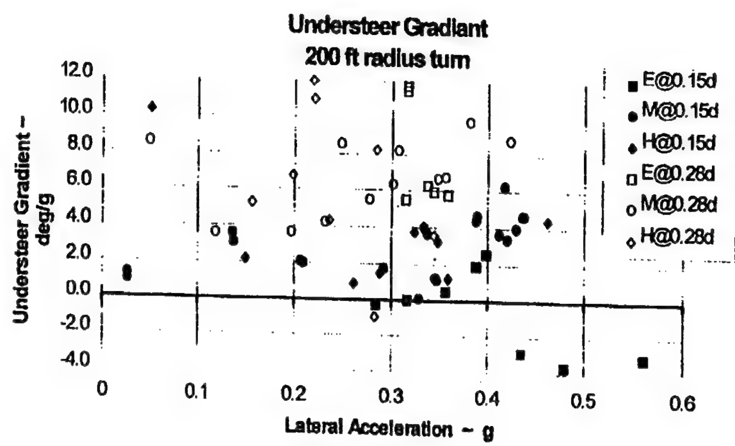
Results of Heavy Truck Testing

- Constant 200 Foot Radius High Coefficient Surface Test at Increasing Speed
- Reduced Results From Speed and Steering Angle Data
- Side-Slip Angle Taken From Water Trace Results

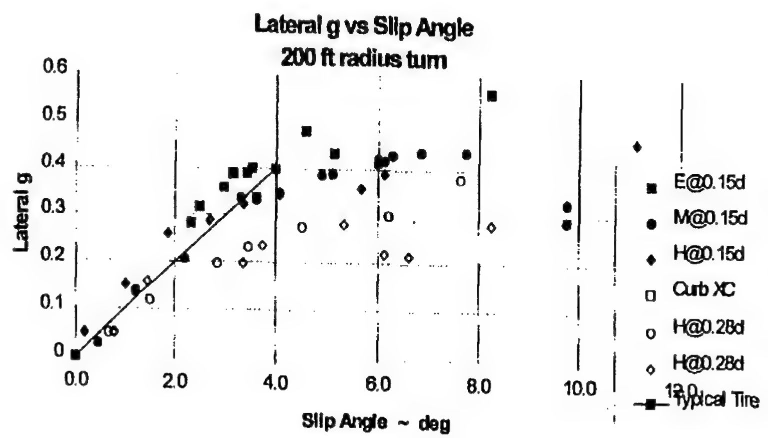
Steering Angle Vs Speed



Understeer Gradient Vs Lateral g



Sideslip Angle Vs Lateral g



Summary Question

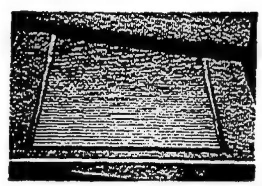
- How to creatively measure/determine sideslip angle?
- Options
  - » Measure slip angle directly
  - » Back calculate for other measurements
    - – Example: Side-slip is the ratio of longitudinal to lateral acceleration

Weighmat

Bo Underwood
Applied Research Associates, Inc.
Vicksburg, Mississippi

What's a Weighmat?

- 2024 Piezo-resistive sensels
- Measures dynamic pressure distributions
- Nonlinear, hysteretic, temperature-sensitive response, but repeatable.



APPLIED RESEARCH ASSOCIATES, INC.

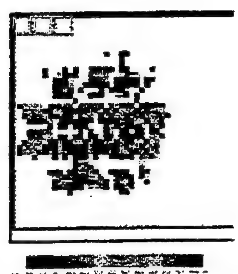
Vehicle Weighing

- Moving or Stationary
- Large and small, high and low pressure tires
- Accuracy within 10%

APPLIED RESEARCH ASSOCIATES, INC

Contact Signatures

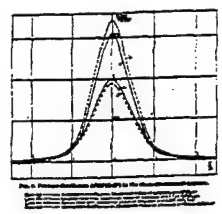
- Contact area
- Pressure distribution
- Static or dynamic



RESEARCH ASSOCIATES, INC

Weighmat Possibilities

- Subsurface measurements
  - Soils
  - Pavements
- Screening/Gating
  - Weight enforcement
  - Vehicle identification

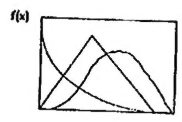


a

Insights from Stochastic Mobility Modeling

Presented by: Niki C. Deliman

Project Associates: Richard Ahlvin, Laura Bunch, George Mason, Jody Priddy, Jeff Williamson



b

Issues

- What factors most influence speed outcomes?
- How do changes in input parameters and empirically derived results affect speed predictions and measures of performance?
- How "good" do inputs need to be?
- How do predicted and actual measured speeds compare?
- How do deviations in predicted and actual speeds affect measures of performance and decision aids?
- What range in speeds and derived measures of performance is expected in practice?
- What areas of mobility modeling need to be improved?

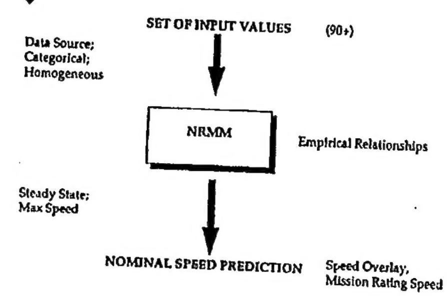
c

Research Objectives

- Assume model predictions are accurate: Incorporate uncertainty into speed predictions
  - range of speed predictions for one vehicle - terrain unit combination
  - determine influential factors
  - obtain better quantified predictions
- Assume model inputs are accurate: Model actual speed distribution as a function of deterministic predicted speeds
  - E[M | P=p]
  - VAR[M | P=p]
  - generate risk-based decision aids

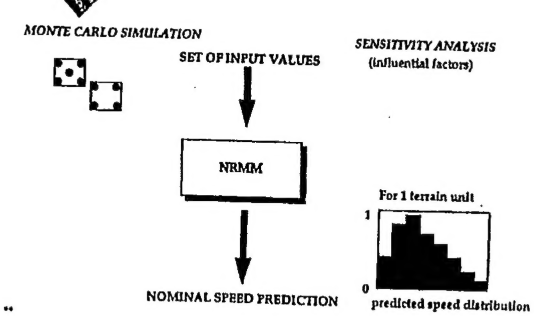
d

Deterministic Speed Predictions



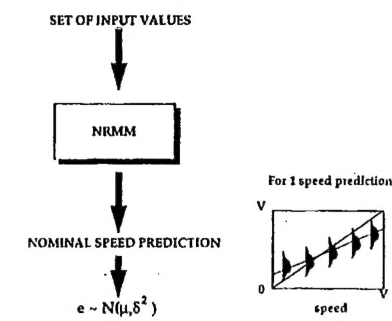
a

Approach: Inputs as Random Variables



b

Approach: Outputs as Random Variables



c

Results - Inputs as Random Variables

- All parameters are important for some combination of vehicle-terrain factors
- Historic study showed that vehicle rankings were not changed by stochastic analysis (Lessem et al., 1993)
- Associated risk apparent
- Distribution functions for speed are not necessarily symmetrically distributed
- Empirical relationships for DBP vs. slip in fine grained soils are conservative
- Need more testing for tracked vehicle traction on course grained soils

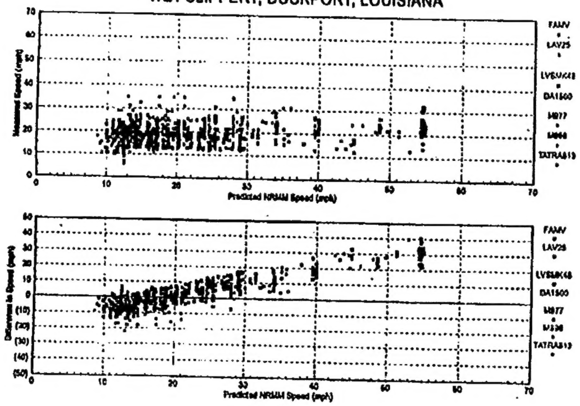
d

Results - Outputs as Random Variables

- Inconsistent bias in expected speeds:
  - underpredict at low speeds
  - overpredict at high speeds
- Conditional speeds can be modeled by a normal distribution
- Deviation from predicted speeds differs for wheeled and tracked vehicles, road type, and scenario (32 categorizations)
- Current acceleration/deceleration algorithms do not model events well
- Where obstacles or vegetation stem spacing are speed controlling factor, there is poor correlation between measured and predicted speeds

a VARIANCE IN SPEEDS: WHEELED VEHICLES

WET-SLIPPERY, DUCKPORT, LOUISIANA

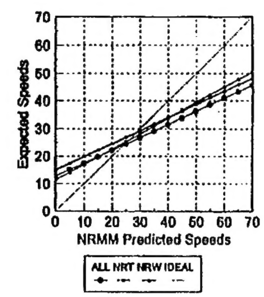


b EXPECTED SPEEDS

- Roads, Normal Conditions

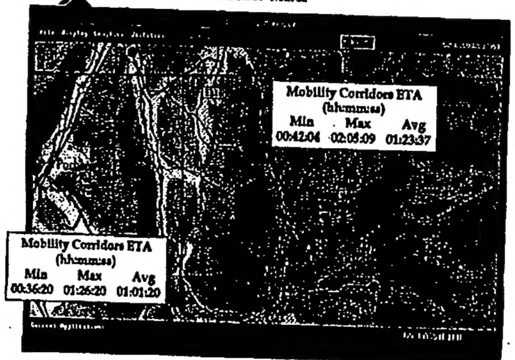
- EQUATIONS
  - Tracks (NOT)
    - M = P - (-12.8 + 0.53 * P)
  - ✓ Tracks, Normal (NRT)
    - ✓ M = P - (-11.33243 + 0.43875 * P)
  - ✓ Wheeles, Normal (NRW)
    - ✓ M = P - (-15.131337 + 0.52899 * P)

8.20	7.27	9.83



c

AREA: KOREA VEHICLE: M1A1



Two Routes from Point A To B Showing ETA Differences.

d Summary

- Stochastic (risk-based) mobility predictions provide valuable information beyond the deterministic value
- Work has been well received
  - requested to participate in evaluation exercise
  - subject of an article in <u>Armor</u>
  - USAES interest in utilizing results
  - constructive feedback from ALMC officers
  - participating in OACs
  - utilizing concepts in procurement and vehicle comparison (NSWC)

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During a 3-day period, beginning March 13, 1996, the U.S. Army Engineer Waterways Experiment Station (WES), Mobility Systems Division, hosted a workshop to solicit expert opinions on where the virtual proving grounds are today and where they will be in the future. Three questions were asked at the start of the workshop: (a) what are todays capabilities in off-road virtual environments, (b) where the virtual proving grounds will be in the next 5 years, (c) and what are the technical barriers that would prevent these goals? WES invited leaders for the Industry, University, and Government to work together for 3 days to give their opinions and lend their technical expertise on the answers to these questions. This report documents the proceedings of that workshop.

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